

Appendix A Detailed Model Description

This report describes the variables, constraints, and other attributes in the linear program formulation of ReEDS. It outlines, in order:

1. Subscripts (variables and constraints)
2. Major decision variables
3. The objective function
4. Constraints
5. Glossary of parameters

A.1 Subscripts

Variables, parameters, and constraints are all subscripted to describe the space over which they apply. The various sets are listed below.

A.1.1 Geographical Sets:

- i, j —356 supply/demand regions track where wind and solar power are generated and to where they are transmitted. Source regions are generally noted ‘ i ’ and destinations, ‘ j .’
- n, p —134 balancing authorities (abbreviated PCA, for Power Control Authority), each of which contains one or more supply/demand regions, track conventional generation. Source regions are generally noted ‘ n ’ and destinations, ‘ p .’
- $states$ —There are 48 states (no Alaska or Hawaii).
- rto —32 regional transmission organizations, each of which contains one or more balancing authorities. Reserve margin requirements, operating reserve requirements, and wind curtailments are monitored at the RTO level.
- r —There are 13 nerc regions/subregions.
- in —There are 3 interconnects.

A.1.2 Temporal Sets:

- $year$ —2006 to 2050.
- $period$ —There are 23 2-year periods.
- s —4 annual seasons.
- m —16 time-slices during each year, with four seasons and four daily time-slices in each season plus one superpeak time-slice. (Spring has only 3 slices.)

A.1.3 Other Sets:

- c —5 wind classes.
- l —3 wind locations (*onshore*, *shallow offshore*, *deep offshore*).
- $wscp$ —level of wind supply curve.
- g, bp —wind growth bracket and break points.

- *ginst*, *bpinst*—wind installations growth bracket and break points.
- *cCSP*—5 Concentrated Solar Power (CSP) classes.
- *cspscp*—level of csp supply curve.
- *gCSP*, *bpCSP*—CSP growth bracket and break points.
- *gCSPinst*, *bpCSPinst*—CSP installations growth bracket and break points.
- *escp*—level of intraregion electricity supply curve.
- *bioclass*—level of biomass supply curve.
- *geoclass*—level of geothermal resource supply curve.
- *egsclass*—level of conductive Enhanced Geothermal Systems (EGS) supply curve.
- *tpca_g*, *tpcabp*—transmission growth bracket and break points.
- *pol*—4 pollutants (SO_2 , NO_x , Hg , CO_2).
- *q*—Conventional generating technologies:
 - hydropower
 - natural gas
 - combustion turbine
 - combined cycle
 - combined cycle with carbon capture and sequestration (CCS)
 - coal
 - traditional pulverized coal, unscrubbed, scrubbed, or cofiring
 - modern pulverized, with or without cofiring
 - integrated gasification combined cycle (IGCC) with or without CCS
 - oil-gas-steam
 - nuclear
 - dedicated biomass
 - geothermal
 - landfill gas/municipal solid waste
 - others (distributed PV).
- *st*—There are 4 storage technologies:
 - pumped hydropower (PHS)
 - batteries
 - compressed air energy storage (CAES).
 - ice-storage

A.2 Major Decision Variables

The major decision variables include capacity of conventionals, renewables, and storage along with transmission; and dispatch of conventional capacity and storage. Unless otherwise noted, capacity variables are expressed in megawatts and energy variables are expressed in megawatt-hours.

Wind Variables

- $WturN_{c,i,l,wscp}$ — new³ wind capacity that will access pre-2006⁴ transmission lines at a cost associated with step $wscp$ of the transmission supply curve.⁵
- $WturTN_{c,i,l}$ — New wind turbine capacity that can be transmitted only on new transmission lines dedicated to wind transmission from region i to another region.
- $Wtur_inregion_{c,i,l}$ — New wind turbine capacity whose transmitted electricity will move on new transmission lines dedicated to wind from a class c wind site within region i to a load center also within region i .
- $WN_{c,i,j,l}$ — Wind energy sent from new turbines in region i to region j that must be accommodated on pre-2006 lines.
- $WTN_{c,i,j,l}$ — Wind energy sent from new turbines in region i to region j on new lines dedicated to wind.
- $Welec_inregion_{c,i,l,escp}$ Wind energy sent from new turbines in region i to a load center also within region i .
- $WSurpLess_{n,m}$ — The statistically calculated amount by which wind power supplied to balancing area n exceeds the electricity demand in time-slice m
- WCt_g — New national wind turbine capacity in bin g ; used for estimating the increase in wind turbine price with rapid world growth.
- $WCtinst_{i,ginst}$ — New wind turbine capacity from bin $ginst$ in region i ; used for estimating the increase in installation costs with rapid regional growth.
- $WNSC_{i,l,wscp}$ — New wind turbine capacity to be connected to the grid in region i from step $wscp$ of the supply curve, which provides the cost of building transmission from region i to the grid.

CSP Variables

- $CSpturN_{cCSP,i,cspscp}$ — new CSP capacity that will access pre-2006 transmission lines at a cost associated with step $cspscp$ of the transmission supply curve.
- $CSpturTN_{cCSP,i,j}$ — New CSP capacity that can be transmitted only on new transmission lines dedicated to CSP transmission from region i to another region.
- $CSptur_inregion_{cCSP,i}$ — New CSP capacity whose transmitted electricity will move on new transmission lines dedicated to CSP from a class $cCSP$ site within region i to a load center also within region i .
- $CSPN_{cCSP,i,j}$ — CSP energy sent from new plants in region i to region j that must be accommodated on pre-2006 lines.

³New capacity means capacity built in this period, i.e. in this period's optimization run of the linear program.

⁴To reduce confusion, in the detailed model description, existing prior to the start of the model (2006) will be called "pre-2006" while existing prior to the start of a given period will be called "existing."

⁵In the model itself, $WturN$, $WturTN$, WN , and WTN are not actually subscripted with c . Instead, to reduce the solve time, a parameter $class_{c,i,l}$ keeps track of which class is the most attractive available in each region in that period. For this document, $class_{c,i,l}$ has been elided and c has been integrated directly into the variables for simplicity.

- $\text{CSPTN}_{cCSP,i,j}$ — CSP energy sent from new plants in region i to region j on new lines dedicated to CSP.
- $\text{CSPElec_inregion}_{cCSP,i,escp}$ — CSP energy sent from new plants in region i to a load center also within region i .
- CSPCt_{gCSP} — New national CSP capacity in bin $gCSP$; used for estimating the increase in CSP price with rapid world growth.
- $\text{CSPCtinst}_{i,gCSPinst}$ — New CSP capacity from bin $gCSPinst$ in region i ; used for estimating the increase in installation costs with rapid regional growth.
- $\text{CSPNSC}_{cspscp,i}$ — New CSP capacity to be connected to the grid in region i from step $cspscp$ of the supply curve, which provides the cost of building transmission from region i to the grid.
- $\text{ReT}_{n,p}$ — New transmission capacity for wind or CSP (renewable) between balancing areas n and p .

Conventional Variables

- $\text{CONV}_{n,q}$ — Dispatchable (primarily conventional) capacity of technology q in balancing area n .⁶
- $\text{CONVgen}_{n,m,q}$ — Conventional generation in time-slice m by technology q in balancing area n .
- $\text{CONVP}_{n,m,q}$ — Peaking conventional generation in time-slice m by technology q in balancing area n .
- $\text{CCt}_{g,q}$ — Growth in conventional capacity per year.
- $\text{SR}_{n,m,q}$ — Spinning reserve capacity in time-slice m by technology q in balancing area n .
- $\text{QS}_{n,q}$ — Available quickstart capacity of technology q in balancing area n .
- $\text{CONVT}_{n,p,m}$ — New transmission capacity for conventionals between balancing areas n and p .
- $\text{GeoBin}_{geoclass,n}$ — New geothermal capacity by step on resource supply curve.
- $\text{GeoEGSBin}_{egsclass,n}$ — New EGS capacity by step on resource supply curve.
- $\text{BioBin}_{bioclass,n}$ — Biomass consumption by step on resource supply curve.
- $\text{BioGeneration}_{bioclass,n}$ — Generation from dedicated biomass plants by step on resource supply curve.
- $\text{CofireGen}_{bioclass,n}$ — Biomass-generated energy from coal-cofiring plants by step on resource supply curve.

Storage Variables

⁶Note that, for conventional capacity, the decision variable is not the new capacity, but the total capacity. This was done to simplify bookkeeping and to eliminate the need for vintaging of capacity built after 2006. To ensure that conventional capacity from previous periods (minus retirements) is built, a lower bound is specified for each of these variables. Thus the objective function value from the LP includes the full cost of all conventional capacity as well as the cost of their operation over the 20-year investment analysis period. This does not affect the amount of conventional capacity installed, because anything built beyond the lower bound must pay the marginal cost of new capacity. It does affect the amount of conventional fuel purchased, in that any capacity built in previous periods will have the same heatrate as the new capacity.

- $\text{STOR}_{n,st}$ — Load-sited storage capacity of technology st in balancing area n .
- $\text{STORin}_{n,m,st}$ — Energy used to charge load-sited storage in time-slice m .
- $\text{STORout}_{n,m,st}$ — Energy discharged from load-sited storage in time-slice m .
- $\text{STORor}_{n,m,st}$ — Operating reserve capacity of load-sited storage in time-slice m .

Miscellaneous Variables

- $\text{TPCAN}_{n,p}$ — Transmission capacity between balancing areas n and p .
- $\text{TPCACT}_{tpca,g}$ — Growth in new transmission capacity per year.
- $\text{CONTRACTcap}_{n,p}$ — Firm capacity contracted from balancing authority n to p .
- $\text{COALLOWSUL}_{n,q}$ — Annual generation from low-sulfur coal by (coal-burning) technology q .
- RPS_shortfall — Unmet amount of RPS requirement. A penalty is assessed on the shortfalls in the objective function.
- $\text{St_RPS_shortfall}_{states}$ — Unmet amount of state RPS requirement.
- $\text{St_CSPRPS_shortfall}_{states}$ — Unmet amount of state CSP requirement.
- $\text{Oper_Res_Req}_{rto,m}$ — Operating reserve capacity required in rto rto .

A.3 Objective Function

In the objective function we minimize the following costs:

$$\begin{aligned}
 z = & \text{Capital and operating costs of new wind plants} \\
 & + \text{Cost of new transmission for wind} \\
 & + \text{Capital and operating costs of new CSP plants} \\
 & + \text{Cost of new transmission for CSP} \\
 & + \text{Capital cost of conventional generators} \\
 & + \text{Fuel and operating costs of conventional generation} \\
 & + \text{Capital cost of new transmission lines} \\
 & + \text{Capital cost of new storage capacity} \\
 & + \text{Fuel and operating costs of storage} \\
 & + \text{Cost of a CO}_2 \text{ tax}
 \end{aligned}$$

In equation form, with explanatory notes in brackets (below the lines to which they refer):^{7 8}

$$\begin{aligned}
 z = & \sum_{c,i,l} (WturN_{c,i,l} + WturTN_{c,i,l} + Wtur_inregion_{c,i,l}) \\
 & \cdot \left(\begin{aligned} & CW_c \cdot cpop_{c,i,l} \cdot (1 + cslope_{c,i,l} \cdot Cost_Inst_Frac) \\ & \cdot (1 - st_Invincent_{i \in states}) \\ & + CWOM_c + CF_{c,l} \cdot (1 - st_Prodincent_{i \in states}) \end{aligned} \right) \\
 & \text{[wind capital and O\&M costs]} \\
 + & \sum_{c,i,l} \left(\sum_j (WN_{c,i,j,l} + WTN_{c,i,j,l}) + Welec_inregion_{c,i,l} \right) \cdot GridConCost \\
 & \text{[wind capital and O\&M costs]} \\
 + & \sum_{c,i,j,l} WN_{c,i,j,l} \cdot CF_{c,l} \cdot (TOWCOST \cdot Distance_{ij} + PostStamp_{ij}) \\
 & \cdot (1 - SurplusMar_{c,i}) \cdot 8760/CRF \\
 & \text{[cost to connect wind to grid on pre-2006 lines]} \\
 + & \sum_{c,i,l} WTN_{c,i,j,l} \cdot TNWCOST \cdot Distance_{ij} \\
 & \text{[cost to connect wind to grid on new lines]} \\
 + & \sum_g WCt_g \cdot CG_g \\
 & \text{[excessive growth penalty on wind turbines]} \\
 + & \sum_{ginst,i} WCtinst_{ginst,i} \cdot CGinst_{ginst} \\
 & \text{[excessive growth penalty on wind installation]}
 \end{aligned}$$

⁷some subscripts, e.g. $wscp$ on $WturN$ in the first line of the objective function are elided here and in constraints, below, when they are immediately summed over and therefore have no bearing on the equation.

⁸All parameters used in the objective function and constraints can be found in the glossary, below.

$$\begin{aligned}
& + \sum_{c,i,l} \left(\sum_{wscp} \text{WNSC}_{i,l,wscp} \cdot \text{WR2GPTS}_{c,i,l,wscp} \right) \cdot CF_{c,l} \cdot 8760 / CRF \\
& \quad \text{[cost of spur line to connect new wind capacity to pre-2006 grid]} \\
& + \sum_{c,j,l} \left(\sum_{escp} \text{Welec_inregion}_{c,j,l,escp} \cdot \text{MW_inregion_dis}_{c,j,escp} \right) \cdot CF_{c,l} \cdot 8760 / CRF \\
& \quad \text{[cost of spur line to connect new wind capacity to inregion load]} \\
& + \sum_{cCSP,i} \left(\text{CSPturN}_{cCSP,i} + \text{CSPturTN}_{cCSP,i} + \text{CSPtur_inregion}_{cCSP,i} \right) \cdot (\text{CCSP}_{cCSP} + \text{CSPOM}_{cCSP}) \\
& \quad \text{[CSP capital and O\&M costs]} \\
& + \sum_{cCSP,i,j} \left(\text{CSPN}_{cCSP,i,j} + \text{CSPTN}_{cCSP,i,j} + \text{CSPelec_inregion}_{cCSP,i,j} \right) \cdot \text{CSPGridConCost} \\
& \quad \text{[inregion CSP capital and O\&M costs]} \\
& + \sum_{cCSP,i,j,m} \text{CSPN}_{cCSP,i,j} \cdot H_m \cdot CF_{cCSP,m} \cdot (\text{TOWCOST} \cdot \text{Distance}_{i,j} + \text{PostStamp}_{i,j}) \\
& \quad \cdot (1 - \text{CSPSurplusMar}_{cCSP,i}) / CRF \\
& \quad \text{[cost to connect CSP to grid on pre-2006 lines]} \\
& + \sum_{cCSP,i,j} \text{CspTN}_{cCSP,i,j} \cdot \text{TNWCOST} \cdot \text{Distance}_{i,j} \\
& \quad \text{[cost to connect CSP to grid on new lines]} \\
& + \sum_{cCSP,i,j,m} \left(\sum_{cspscp} \text{CspNSC}_{cCSP,i,cspscp} \cdot \text{CSP2GPTS}_{cCSP,i,cspscp} \right) \cdot CF_{cCSP,m} \cdot H_m / CRF \\
& \quad \text{[cost of spur line to connect new wind capacity to pre-2006 grid]} \\
& + \sum_{cCSP,i,j,m} \left(\sum_{escp} \text{CspELEC_inregion}_{cCSP,j,escp} \cdot \text{CSP_inregion_dis}_{cCSP,j,escp} \right) \cdot \frac{CF_{cCSP,m} \cdot H_m}{CRF} \\
& \quad \text{[cost of spur line to connect new CSP capacity to inregion load]} \\
& + \sum_{gCSP} \text{CSPCt}_{gCSP} \cdot \text{CGcsp}_{gCSP} \\
& \quad \text{[excessive growth penalty on CSP hardware]} \\
& + \sum_{gCSPinst,i} \text{CSPCtinst}_{gCSPinst,i} \cdot \text{CGcspinst}_{gCSPinst} \\
& \quad \text{[excessive growth penalty on CSP installation]} \\
& + \sum_{n,q} \text{CONV}_{n,q} \cdot (\text{CCONV}_q + \text{CCONVF}_q + \text{Ctranadder}_q + \text{GridConCost}) \\
& \quad \text{[capital and O\&M costs for conventional generators]} \\
& + \sum_{n,p} \text{CONVT}_{n,p,m} \cdot H_m / CRF \cdot (\text{TOCOST} \cdot \text{Distance}_{n,p} + \text{PostStamp}_{n,p}) \\
& \quad \text{[variable costs for transmission]} \\
& + \sum_{q,g} \text{CGconv}_{q,g} \cdot \text{CCt}_{q,g}
\end{aligned}$$

$$\begin{aligned}
& \text{[excessive growth penalty on conventional capacity]} \\
+ & \sum_{n,p} \text{TPCAN}_{n,p} \cdot \text{TNCOST} \cdot \text{Distance}_{n,p} \\
& \text{[capital cost of new transmission lines]} \\
+ & \sum_{\text{TPCA}_G} \text{TPCA_CG}_{\text{TPCA}_G} \cdot \text{TPCA_Ct}_{\text{TPCA}_G} \\
& \text{[excessive growth penalty on new transmission]} \\
+ & \sum_{n,m,q} \text{CONVgen}_{n,m,q} \cdot H_m \cdot \text{CCONVV}_{n,q} \\
& \text{[operating and fuel costs for conventional generators]} \\
+ & \sum_{n,m,q} \text{CONVP}_{n,m,q} \cdot H_m \cdot \text{CCONVV}_{n,q} \cdot \text{PcostFrac}_q \\
& \text{[increased operating cost for peaking power]} \\
+ & \sum_{n,m,q} \text{SR}_{n,m,q} \cdot H_m \cdot \text{CSR}_{n,q} \\
& \text{[operating and fuel costs for spinning reserve]} \\
+ & \sum_{n,q} \text{QS}_{n,q} \cdot \text{CQS} \\
& \text{[cost for quickstart capacity]} \\
+ & \sum_{\text{geoclass},n} \text{GeoBin}_{\text{geoclass},n} \cdot \text{GeoAdder}_{\text{geoclass},n} \cdot \text{CCONV}_{\text{geothermal}} / \text{CCC}_{\text{geothermal}} \\
+ & \sum_{\text{egsclass},n} \text{GeoEGSBin}_{\text{egsclass},n} \cdot \text{GeoAdder}_{\text{egsclass},n} \cdot \text{CCONV}_{\text{geothermal}} / \text{CCC}_{\text{geothermal}} \\
& \text{[supply curve-based cost for geothermal capacity]} \\
+ & \sum_{\text{bioclass},n} \text{BioGeneration}_{\text{bioclass},n} \cdot \text{CHeatRate}_{\text{biopower}} \cdot \text{BioFeedstockLCOF}_{\text{bioclass},n} \\
+ & \sum_{\text{bioclass},n} \text{CofireGen}_{\text{bioclass},n} \cdot \text{CHeatRate}_{\text{cofire}} \cdot (\text{BioFeedstockLCOF}_{\text{bioclass},n} - \text{Fprice}_{\text{coal},n}) \\
& \text{[supply curve-based cost for biomass feedstock]} \\
+ & \sum_{\text{st},n} \text{STOR}_{\text{st},n} \cdot (\text{CSTOR}_{\text{st}} + \text{FSTOR}_{\text{st}} / \text{CRF}) \\
& \text{[capital and O\&M costs for storage]} \\
+ & \sum_{n,m,\text{st}} \text{STORin}_{n,m,\text{st}} \cdot H_m \\
& \quad \cdot (\text{VSTOR}_{\text{st}} \cdot \text{STOR_RTE}_{\text{st}} + \text{Fprice}_{\text{CAES},n} \cdot \text{CAESHeatRate}) \\
& \text{[operating and fuel costs for storage]} \\
+ & \sum_{\text{st},\text{storagebp}} \text{STORAGEBIN}_{\text{st},\text{storagebp}} \cdot \text{CGStorage}_{\text{st},\text{storagebp}} \\
& \text{[excessive growth penalty on new storage]} \\
+ & \sum_{n,m,q} (\text{CONVgen}_{n,m,q} + \text{CONVP}_q) \cdot H_m \cdot \text{CONVpol}_{q,\text{CO}_2} \cdot \text{CHeatRate}_q \cdot \text{CarbTax} \\
& \text{[cost of carbon tax on conventional generation]} \\
+ & \sum_{n,m,\text{st}} \text{STORout}_{n,m,\text{st}} \cdot H_m \cdot \text{STORpol}_{\text{st},\text{CO}_2} \cdot \text{CHeatRate}_{\text{st}} \cdot \text{CarbTax} \\
& \text{[cost of carbon tax on storage generation]}
\end{aligned}$$

$$\begin{aligned}
& + \sum_{n,q} \text{COALLOWSUL}_{n,q} \cdot \text{lowsuladd_LCF}_n \cdot \text{CHeatRate}_q \\
& \quad \text{[surcharge for using low sulfur coal]} \\
& + \text{RPS_shortfall} \cdot \text{RPSSCost} \\
& + \sum_{states} \text{St_RPSshortfall}_{states} \cdot \text{St_RPSSCost} \\
& + \sum_{states} \text{St_CSPRPSshortfall}_{states} \cdot \text{St_CSPRPSCost}_{states} \\
& \quad \text{[costs of shortfalls in failing to meet RPS requirements]}
\end{aligned}$$

A.4 Constraints

The minimization of cost in ReEDS is subject to a large number of different constraints, involving limits on resources, transmission constraints, national growth constraints, ancillary services, and pollution. Unless specifically noted otherwise (see, for example, the wind resource limit below), these constraints apply to new generating capacity built in the time period being optimized.

The constraint name is shown with the subscripts over which the constraint applies. For example, in the constraint immediately below, the subscript ‘ c, i, l ’ immediately following the name of the constraint implies that this constraint is applied for every class of wind c , every region i , and every location l . Because there are 356 regions, five classes of wind, and 3 locations, this first type of constraint is repeated 5,340 times (356x5x3).

A.4.1 Constraints on Wind

Wind Resource Constraint: For every wind class c and wind supply region i , the sum of all wind capacity installed in this and preceding time periods must be less than the total wind resource in the region.

$WIND_RES_UC_{c,i,l}$

$$\text{WturN}_{c,i,l} + \text{WturTN}_{c,i,l} + \text{Wtur_inregion}_{c,i,l} \leq \max(0, \text{WRuc}_{c,i,l} - \text{WturO}_{c,i,l} - \text{WTturO}_{c,i,l})$$

Wind Supply Curve: New wind of class c in region i at interconnection cost step $wscp$ must be less than the remaining wind resource in that cost step.⁹ The second constraint balances the wind on pre-2006 lines across the different supply curve points and is used to determine the cost of transmission required to reach the grid.

$WIND_supply_curves_{c,i,l,wscp}$

$$\text{WturN}_{c,i,l,wscp} \leq \max(0, \text{WR2G}_{c,i,l,wscp})$$

$WIND_EXISTRANS_BALANCE_{i,l}$

$$\sum_{wscp} \text{WNSC}_{i,l,wscp} = \sum_j \text{WN}_{i,j,l}$$

⁹A preliminary optimization is performed outside and prior to the main model to construct a supply curve for onshore wind, shallow offshore wind, and deep offshore wind for each wind class c and region i . This supply curve is comprised of four quantity/cost pairs ($\text{WR2G}_{c,i,l,wscp} / \text{WR2GPTS}_{c,i,l,wscp}$). The “curve” provides the amount of class c wind $\text{WR2G}_{c,i,l,wscp}$ that can be connected to the pre-2006 grid for a cost between $\text{WR2GPTS}_{c,i,l,wscp-1}$ and $\text{WR2GPTS}_{c,i,l,wscp}$. This “pre-LP” optimization is described in more detail in Appendix G. The quantity $\text{WR2G}_{c,i,l,wscp}$ is reduced after each period’s LP optimization by the amount of wind used in the time period from that cost step.

Wind Transmission Constraint: The new class c wind transmitted from a region i to all regions j must be less than or equal to the total amount of new region i class c wind used from the class c wind supply curve.

$WIND_2_GRID_{c,i,l}$

$$\sum_j WN_{c,i,j,l} \leq \sum_{wscp} WturN_{c,i,l,wscp}$$

$WIND_2_NEW_{c,i,l}$

$$\sum_j WTN_{c,i,j,l} \leq \sum_{wscp} WturTN_{c,i,l,wscp}$$

$WIND_INREGION_{c,i,l}$

$$\sum_{escp} Welec_inregion_{c,i,l,escp} \leq Wtur_inregion_{c,i,l}$$

Wind Growth Constraint: These two constraints allocate new wind capacity (MW) to bins that have turbine prices that are higher than the costs during periods of rapidly growing demand. The bins are defined as a fraction of the national wind capacity (MW) at the start of the period.

$WIND_GROWTH_TOT$

$$\sum_{c,i,l} (WturN_{c,i,l} + WturTN_{c,i,l} + Wtur_inregion_{c,i,l}) \leq \sum_g WCt_g$$

$WIND_GROWTH_BIN_g$

$$WCt_g \leq Gt_g \cdot BASE_WIND$$

Wind Installation Growth Constraint: These two constraints allocate new wind capacity (MW) to bins that have installation costs associated with them over and above the base costs of installation. The bins are defined as a fraction of the regional wind capacity (MW) at the start of the period.

$WIND_GROWTH_INST_i$

$$\sum_{c,l} (WturN_{c,i,l} + WturTN_{c,i,l} + Wtur_inregion_{c,i,l}) - 200 \leq \sum_{ginst} WCtinst_{i,ginst}$$

$WIND_GROWTH_BIN_INST_{i,ginst}$

$$WCtinst_{i,ginst} \leq Gtinst_{ginst} \cdot BASE_WIND_inst_i$$

Wind Curtailments: This constraint defines wind curtailments based on a statistical approach. SurplusOld and SurplusMar are calculated in between investment periods based on a statistical approach and as described in Appendix D. The last term on the right hand side reduces the amount of curtailed wind power if new storage is built in balancing area n . $WSurpLess_{n,m}$ is then subtracted from the wind contribution to meeting the $LOAD_PCA$ constraint for time-slice m and for the RPS requirement.

$$WIND_RECOVERY_{n,m}$$

$$\begin{aligned} WSurpLess_{n,m} &\geq SurplusOld_{n,m} \\ &+ \sum_{c,i,j,l}^{j \in n} (WN_{c,i,j,l} + WTN_{c,i,j,l} + Welec_inregion_{c,j,l}) \cdot (1 - TWLOSSnew \cdot Distance_{ij}) \cdot SurplusMar_{n,m} \\ &- \sum_{st} SurplusRecoveryPerStorage_{n,m} \cdot STOR_{n,st} \end{aligned}$$

A.4.2 Constraints on CSP

CSP Resource Limit: For every CSP class and supply region i , the sum of all CSP capacity installed in this and preceding time periods must be less than the total solar resource in the region.

$$CSP_REC_UC_{cCSP,i}$$

$$\begin{aligned} CSPTurN_{cCSP,i} + CSPTurTN_{cCSP,i} + \\ CSPTur_inregion_{cCSP,i} \leq \max(0, CSPRuc_{cCSP,i} - CSPTurO_{cCSP,i} - CSPTurO_{cCSP,i}) \end{aligned}$$

CSP Supply Curve: New CSP of class $cCSP$ in region i at interconnection cost step $cspscp$ must be less than the remaining solar resource in that cost step. The second constraint balances the CSP on pre-2006 lines across the different supply curve points and is used to determine the cost of transmission required to reach the grid.

$$CSP_supply_curves_{cCSP,i,cspscp}$$

$$CSPTurN_{cCSP,i,cspscp} \leq \max(0, CSP2G_{cCSP,i,cspscp})$$

$$CSP_EXISTRANS_BALANCE_i$$

$$\sum_{cspscp} CspNSC_{i,cspscp} = \sum_j CspN_{ij}$$

CSP Transmission Constraints: New CSP transmitted from a region i to all regions j must be less than or equal to the total amount of new region i CSP used from the solar supply curve.

$$CSP_2_GRID_{cCSP,i}$$

$$\sum_j CSPN_{cCSP,i,j} \leq \sum_{cspscp} CSPTurN_{cCSP,i,cspscp}$$

$$CSP_2_NEW_{cCSP,i}$$

$$\sum_j CSPTN_{cCSP,i,j} \leq \sum_{cspscp} CSPTurTN_{cCSP,i,cspscp}$$

$$ELEC_inregion_{cCSP,i}$$

$$\sum_{escp} CSPELEC_inregion_{cCSP,i,escp} \leq CSPTur_inregion_{cCSP,i}$$

CSP Growth Constraint: These two constraints allocate new CSP capacity (MW) to bins that have plant costs associated with them over and above the costs of the solar plants themselves. The bins are defined as a fraction of the national CSP capacity (MW) at the start of the period.

$$CSP_GROWTH_TOT$$

$$\sum_{cCSP,i} (CSPturN_{cCSP,i} + CSPturTN_{cCSP,i} + CSPtur_inregion_{cCSP,i}) \leq \sum_{gCSP} CSPCt_{gCSP}$$

$$CSP_GROWTH_BIN_{gCSP}$$

$$CSPCt_{gCSP} \leq GtCSP_{gCSP} \cdot BASE_CSP$$

CSP Installation Growth Constraint: These two constraints allocate new CSP capacity (MW) to bins that have installation costs associated with them over and above the base costs of installation. The bins are defined as a fraction of the regional CSP capacity (MW) at the start of the period.

$$CSP_GROWTH_INST_i$$

$$\sum_{cCSP} (CSPturN_{cCSP,i} + CSPturTN_{cCSP,i} + CSPtur_inregion_{cCSP,i}) - 200 \leq \sum_{gCSPinst} CSPCtinst_{i,gCSPinst}$$

$$CSP_GROWTH_BIN_INST_{i,gCSPinst}$$

$$CSPCtinst_{i,gCSPinst} \leq GtCSPinst_{gCSPinst} \cdot BASE_CSP_inst_i$$

A.4.3 General Renewable Constraints

State RPS Requirement: This allows the model to include state Renewable Portfolio Standards (RPS), wherein the total annual renewable generation must exceed a specified fraction of the state electricity load or a penalty must be paid on the shortfall.

$ST_RPSConstraint_{states}$

$St_RPSfraction_{states}$

$$\begin{aligned}
\sum_{n,m}^{n \in states} L_{n,m} \cdot H_m &\leq \sum_{c,i,j,m,l}^{j \in states} (WN_{c,i,j,l} + WTN_{c,i,j,l}) \cdot CF_{c,i,m,l} \cdot H_m \\
&\quad \cdot (1 - TWLOSS_{new} \cdot Distance_{i,j})(1 - SurplusMar_{c,j}) \\
&+ \sum_{c,i,j,m}^{j \in states} (WO_{c,i,j,l} + WTO_{c,i,j,l}) \cdot CF_{c,i,m,l} \cdot H_m \\
&\quad \cdot (1 - TWLOSS_{old} \cdot Distance_{i,j})(1 - SurplusOld_{c,j}) \\
&+ \sum_{c,j,m}^{j \in states} Welec_inregion_{c,j,l} \cdot CF_{c,j,m,l} \cdot H_m \\
&\quad \cdot (1 - SurplusMar_{c,j}) \\
&+ \sum_{cCSP,i,j,m}^{j \in states} (CSPN_{cCSP,i,j} + CSPTN_{cCSP,i,j}) \cdot CF_{cCSP,m} \cdot H_m \\
&\quad \cdot (1 - TWLOSS_{new} \cdot Distance_{i,j}) \\
&+ \sum_{cCSP,i,j,m}^{j \in states} (CSPO_{cCSP,i,j} + CSPTO_{cCSP,i,j}) \cdot CF_{cCSP,m} \cdot H_m \\
&\quad \cdot (1 - TWLOSS_{old} \cdot Distance_{i,j}) \\
&+ \sum_{cCSP,j,m}^{j \in states} CSPElec_inregion_{cCSP,j} \cdot CF_{cCSP,m} \cdot H_m \\
&+ \sum_{c,i,m,st}^{j \in states} (WSTORin_wind_{c,i,m,st} + old_WSTORin_wind_{c,i,m,st}) \cdot H_m \\
&+ \sum_{n,m}^{n \in states} (CONV_{n,m,geothermal} + CONVP_{n,m,geothermal}) \cdot H_m \\
&+ \sum_{n,m}^{n \in states} (CONV_{n,m,biopower} + CONVP_{n,m,biopower}) \cdot H_m \\
&+ \sum_{bioclass,n} CofireGen_{bioclass,n} \\
&- \sum_{n,m}^{n \in states} WSurpLess_{n,m} \cdot H_m \\
&+ St_RPS_Shortfall
\end{aligned}$$

RPS Requirement: This allows the model to include a national Renewable Portfolio Standard.

RPSConstraint

RPSfraction

$$\begin{aligned}
& \left(\sum_{c,i,j,m,l} (\text{WN}_{c,i,j,l} + \text{WTN}_{c,i,j,l}) \cdot \text{CF}_{c,i,m,l} \cdot H_m \right. \\
& + \sum_{c,i,j,m,l} (\text{WO}_{c,i,j,l} + \text{WTO}_{c,i,j,l}) \cdot \text{CF}_{c,i,m,l} \cdot H_m \\
& + \sum_{c,j,m,l} \text{Welec_inregion}_{c,j,l} \cdot \text{CF}_{c,j,m,l} \cdot H_m \\
& + \sum_{cCSP,i,j,m} (\text{CSPN}_{cCSP,i,j} + \text{CSPTN}_{cCSP,i,j}) \cdot \text{CF}_{cCSP,m} \cdot H_m \\
& + \sum_{cCSP,i,j,m} (\text{CSPO}_{cCSP,i,j} + \text{CSPTO}_{cCSP,i,j}) \cdot \text{CF}_{cCSP,m} \cdot H_m \\
& + \sum_{cCSP,j,m} \text{CSPelec_inregion}_{cCSP,j} \cdot \text{CF}_{cCSP,m} \cdot H_m \\
& + \sum_{n,m,q} (\text{CONV}_{n,m,q} + \text{CONVP}_{n,m,q}) \cdot H_m \\
& + \sum_{n,m} (\text{STORout}_{n,m,\text{CAES}} - \text{STORin}_{n,m,\text{CAES}}) \cdot H_m \\
& - \sum_{n,m} \text{WSurpLess}_{n,m} \cdot H_m \Big) \\
& \leq \sum_{c,i,j,m,l} (\text{WN}_{c,i,j,l} + \text{WTN}_{c,i,j,l}) \cdot \text{CF}_{c,i,m,l} \cdot H_m \\
& + \sum_{c,i,j,m,l} (\text{WO}_{c,i,j,l} + \text{WTO}_{c,i,j,l}) \cdot \text{CF}_{c,i,m,l} \cdot H_m \\
& + \sum_{c,j,m,l} \text{Welec_inregion}_{c,j,l} \cdot \text{CF}_{c,j,m,l} \cdot H_m \\
& + \sum_{cCSP,i,j,m} (\text{CSPN}_{cCSP,i,j} + \text{CSPTN}_{cCSP,i,j}) \cdot \text{CF}_{cCSP,m} \cdot H_m \\
& + \sum_{cCSP,i,j,m} (\text{CSPO}_{cCSP,i,j} + \text{CSPTO}_{cCSP,i,j}) \cdot \text{CF}_{cCSP,m} \cdot H_m \\
& + \sum_{cCSP,j,m} \text{CSPelec_inregion}_{cCSP,j} \cdot \text{CF}_{cCSP,m} \cdot H_m \\
& + \sum_{n,m} (\text{CONV}_{n,m,\text{hydro}} + \text{CONV}_{n,m,\text{fill}} + \text{CONV}_{n,m,\text{distPV}}) \cdot H_m \\
& + \sum_{n,m} (\text{CONV}_{n,m,\text{geothermal}} + \text{CONVP}_{n,m,\text{geothermal}}) \cdot H_m \\
& + \sum_{n,m} (\text{CONV}_{n,m,\text{biopower}} + \text{CONVP}_{n,m,\text{biopower}}) \cdot H_m \\
& + \sum_{\text{bioclass},n} \text{CofireGen}_{\text{bioclass},n} \\
& - \sum_{n,m} \text{WSurpLess}_{n,m} \cdot H_m \\
& + \text{RPS_Shortfall}
\end{aligned}$$

Limits on Existing Transmission: Due to extant transmission capacity usage and other limitations, the amount of wind power able to be transported on pre-2006 lines is limited. This constraint limits the wind imports on pre-2006 lines to some fraction of the capacity of the transmission lines crossing the boundaries of demand region j .

$WIND_interregion_trans_j$

$$\sum_{c,l} (WN_{c,i,j,l} + WO_{c,i,j,l}) - \sum_{c,l} (WN_{c,j,j,l} + WO_{c,j,j,l}) + \sum_{cCSP,i} (CspN_{cCSP,i,j} + CspO_{cCSP,i,j}) - \sum_{cCSP} (CspN_{cCSP,j,j} + CspO_{cCSP,j,j}) \leq \sum_k a_k \cdot Tk_k$$

Regional Balancing Constraint: This constraint is a transmission capacity balance that defines the transmission capacity needed to handle wind and CSP transmission between balancing authorities. This transmission capacity required for wind/CSP is combined with that required by conventional generation to identify bottlenecks between balancing authorities. The left-hand side of the constraint is the sum of all wind and CSP generation transmitted into the balancing authority plus all that generated within. The right-hand side is the sum of all the wind and CSP generation consumed in- plus all that transmitted from the balancing authority.

$WIND_BALANCE_PCAS_n$

$$\begin{aligned} & \sum_p ReT_{n,p} + \\ & \sum_{c,i,j,l}^{i \in n} (WN_{c,i,j,l} + WO_{c,i,j,l}) + \\ & \sum_{cCSP,i,j}^{i \in n} (CspN_{cCSP,i,j} + CspO_{cCSP,i,j}) = \sum_p ReT_{p,n} \\ & + \sum_{c,i,j,l}^{j \in n} (WN_{c,i,j,l} + WO_{c,i,j,l}) \\ & + \sum_{cCSP,i,j}^{j \in n} (CspN_{cCSP,i,j} + CspO_{cCSP,i,j}) \end{aligned}$$

Conventional Transmission Constraint: Ensures that there is sufficient transmission capacity between contiguous balancing authorities n and p within the same grid interconnect to transmit wind generation and conventional generation in each time-slice m . Transmission capacity added this period is included in both directions p -to- n and n -to- p because transmission lines are bidirectional.¹⁰

$CONV_TRAN_PCA_{n,p,m}$

$$CONVT_{n,p,m} + ReT_{n,p} \leq TPCAN_{n,p} + TPCAN_{p,n} + TPCAO_{n,p}$$

¹⁰The $ReT_{n,p}$ variable prevents ReEDS from shipping wind or CSP from supply region i to the closest demand region j ; and, from there, continue to ship it as conventional power to other balancing authorities where generation is needed. The problem with this is that if new lines are required for this extended wind transmission to a different balancing authority, the wind will not have to pay for a dedicated transmission line, i.e. the transmission line cost will be spread over more hours than only those during which the wind blows.

Contracted Transmission Constraint: Ensures that there is sufficient transmission capacity between contiguous balancing authorities n and p within the same grid interconnect to transmit wind generation and contracted conventional capacity. Transmission capacity added this period is included in both directions p -to- n and n -to- p because transmission lines are bidirectional.

$CONTRACT_TRAN_PCA_{n,p}$

$$CONTRACTcap_{n,p} + WT_{n,p} + CspT_{n,p} \leq TPCAN_{n,p} + TPCAN_{p,n} + TPCAO_{n,p}$$

Transmission Growth Constraints: These two constraints allocate new transmission capacity (MW) to bins that have costs associated with them over and above the cost of the transmission lines themselves. The bins are defined as a fraction of the national transmission capacity at the start of the period.

$TPCA_GROWTH_TOT$

$$TPCAN_{n,p} + \sum_{c,i,j} WTN_{c,i,j} + \sum_{cCSP,i,j} CspTN_{cCSP,i,j} \leq \sum_{TPCA_g} TPCA_Ct_{TPCA_g}$$

$TPCA_GROWTH_BIN_{TPCA_g}$

$$TPCA_Ct_{TPCA_g} \leq TPCA_Gt_{TPCA_g} \cdot BASETPCA$$

A.4.4 Constraints on System Operation

Generation Requirement: This constraint ensures that the load (MW) in time period m in balancing authority n is met with power from conventional and renewable generators plus net imports from balancing authorities contiguous to n ($CONVT_{n,p,m}$). Long-distance transmission from wind and CSP facilities and imports are decremented for transmission losses. Wind and CSP output are also decreased by wind curtailments. Storage can also contribute, but the charging of storage adds to the load requirement.

The $LOAD_PCA$ constraint is the constraint that is affected by the mini-slices; for (n, m) pairs that qualify, it is split into three independent constraints (each with a different set of wind capacity factors) that must be dispatched separately.

$LOAD_PCA_{n,m}$

$$\begin{aligned}
L_{n,m} \leq & \sum_q (\text{CONVgen}_{n,m,q} + \text{CONVP}_{n,m,q}) \\
& + \sum_p (\text{CONVT}_{p,n,m} \cdot (1 - \text{TWLOSS} \cdot \text{Distance}_{n,p}) - \text{CONVT}_{n,p,m}) \\
& + \sum_{c,i,j}^{j \in n} (\text{WN}_{c,i,j,l} + \text{WTN}_{c,i,j,l}) \cdot \text{CF}_{c,i,m,l} \cdot (1 - \text{TWLOSS}_{\text{new}} \cdot \text{Distance}_{i,j}) \\
& + \sum_{c,j,l}^{j \in n} \text{Welec_inregion}_{c,j,l} \cdot \text{CF}_{c,j,m,l} \\
& + \sum_{c,i,j,l}^{j \in n} (\text{WO}_{c,i,j,l} + \text{WTO}_{c,i,j,l}) \cdot \text{CFO}_{c,i,m,l} \cdot (1 - \text{TWLOSS}_{\text{old}} \cdot \text{Distance}_{i,j}) \\
& - \text{WSurpLess}_{n,m} \\
& + \sum_{cCSP,i,j}^{j \in n} (\text{CSPN}_{cCSP,i,j} + \text{CSPTN}_{cCSP,i,j}) \cdot \text{CF}_{cCSP,m} \cdot (1 - \text{TWLOSS}_{\text{new}} \cdot \text{Distance}_{i,j}) \\
& + \sum_{cCSP,j}^{j \in n} \text{CSPelec_inregion}_{cCSP,j} \cdot \text{CF}_{cCSP,m} \\
& + \sum_{cCSP,i,j}^{j \in n} (\text{CSPO}_{cCSP,i,j} + \text{CSPTO}_{cCSP,i,j}) \cdot \text{CF}_{cCSP,m} \cdot (1 - \text{TWLOSS}_{\text{old}} \cdot \text{Distance}_{i,j}) \\
& + \sum_{st} (\text{STORout}_{n,m,st} - \text{STORin}_{n,m,st})
\end{aligned}$$

Reserve Margin Requirement: Ensures that the conventional and storage capacity (MW) and capacity value of wind and CSP during the peak summer period is large enough to meet the peak load plus a reserve margin and any storage input requirements. Peak-load requirements in NERC region r can also be met by contracting for capacity located in other NERC regions.

$$RES_MARG_{rto}$$

$$\begin{aligned}
\sum_n^{n \in rto} P_{rto} \cdot (1 + RM_{rto}) &\leq \sum_{n,q}^{n \in rto} CONV_{n,q} \\
&+ \sum_{c,i,j}^{j \in rto} (WN_{c,i,j} + WTN_{c,i,j}) \cdot CVmar_{c,i,rto} \\
&\quad \cdot (1 - TWLOSS_{new} \cdot Distance_{i,n}) \\
&+ \sum_{c,i,j}^{j \in rto} (WO_{c,i,j} + WTO_{c,i,j}) \cdot CVold_{c,i,rto} \\
&\quad \cdot (1 - TWLOSS_{old} \cdot Distance_{i,n}) \\
&+ \sum_{c,j,escp}^{j \in rto} Welec_inregion_{c,j,escp} \cdot CVmar_{c,i,rto} \\
&+ \sum_{cCSP,i,j}^{j \in rto} (CspN_{cCSP,i,j} + CspTN_{cCSP,i,j}) \cdot CspCVmar_{cCSP,i,rto} \\
&\quad \cdot (1 - TWLOSS_{new} \cdot Distance_{i,n}) \\
&+ \sum_{cCSP,i,j}^{j \in rto} (CspO_{cCSP,i,j} + CspTO_{cCSP,i,j}) \cdot CspCVold_{cCSP,i,rto} \\
&\quad \cdot (1 - TWLOSS_{old} \cdot Distance_{i,n}) \\
&+ \sum_{cCSP,j,escp}^{j \in rto} CSpelec_inregion_{cCSP,j,escp} \cdot CspCVmar_{cCSP,i,rto} \\
&+ \sum_{n,st}^{n \in rto} STOR_{n,st} + old_STOR_{n,st} \\
&+ \sum_{i,st}^{i \in n} WSTORout_inregion_{i,H16,st} + old_WSTORout_inregion_{i,H16,st} \\
&+ \sum_{n,p}^{n \in rto} CONTRACTcap_{p,n} \cdot (1 - TLOSS \cdot Distance_{n,p}) \\
&- \sum_{n,p}^{n \in rto} CONTRACTcap_{n,p}
\end{aligned}$$

Operating Reserve Requirement: Ensures that the spinning reserve, quick-start capacity, and storage capacity are adequate to meet the normal operating reserve requirement and that imposed by wind. The second and third constraints work together to ensure that no more than a set fraction ($qsfrac$) of the operating reserve requirement be met by quickstart capacity.

$$OPER_RES_{rto,m}$$

$$\begin{aligned} Oper_Res_Req_{rto,m} \leq & \sum_{n,q}^{n \in rto} SR_{n,m,q} + QS_{n,q} \cdot F_q \\ & + \sum_{n,st}^{n \in rto} STOR_OR_{n,m,st} + \sum_{i,st}^{i \in rto} WSTOR_OR_{i,m,st} + old_WSTOR_OR_{i,m,st} \end{aligned}$$

$$OPER_RES2_{m,rto}$$

$$\begin{aligned} Oper_Res_Req_{rto,m} = & TOR_{rto,m} \\ & + \sum_{c,j}^{j \in rto} (WN_{i,j} + WTN_{i,j}) \cdot ORmar_{c,i,rto,m} \\ & + \sum_{c,j}^{j \in rto} Welec_inregion_{c,j} \cdot ORmar_{c,j,rto,m} \end{aligned}$$

$$OPER_RES3_{rto,m}$$

$$\sum_{n,q}^{n \in rto} QS_{n,q} \cdot F_q \leq qsfrac \cdot Oper_Res_Req_{rto,m}$$

Spinning Reserve Constraint: Ensures that the useful generation from a conventional plant of type q comprises at least a minimum fraction of the total generation in time-slice m in balancing authority n .

$$SPIN_RES_CAP_{n,m,q}$$

$$SR_{n,m,q} \leq CONVgen_{n,seasonpeak,q} \cdot FSRV_q$$

Capacity Dispatch Constraint: Ensures that the capacity (MW) in balancing authority n of type q —derated by the average forced outage rate for type q generators—is adequate to meet the load, quick-start, and spinning reserve required in time-slice m .

$$CAP_FO_PO_{n,m,q}$$

$$CONVgen_{n,m,q} + SR_{n,m,q} + QS_{n,q} \leq CONV_{n,q} \cdot (1 - FO_q)(1 - PO_{m,q})$$

Peaking Constraint: To prevent unrealistic cycling, base-load plants are constrained in peak time-slices to generate no more electricity than the average of that which is generated in the shoulder time-slices. Additional power is available through $CONVP$, at increased cost.

$B_peak_12_{n,m,q}$

$$\begin{aligned}
CONVgen_{n,H3,q \in baseload} &\leq (CONVgen_{n,H2,q \in baseload} + CONVgen_{n,H4,q \in baseload})/2 \\
CONVgen_{n,H7,q \in baseload} &\leq (CONVgen_{n,H6,q \in baseload} + CONVgen_{n,H8,q \in baseload})/2 \\
CONVgen_{n,H12,q \in baseload} &\leq (CONVgen_{n,H10,q \in baseload} + CONVgen_{n,H11,q \in baseload})/2 \\
CONVgen_{n,H15,q \in baseload} &\leq CONVgen_{n,H14,q \in baseload} \\
CONVgen_{n,H16,q \in baseload} &\leq (CONVgen_{n,H2,q \in baseload} + CONVgen_{n,H4,q \in baseload})/2
\end{aligned}$$

Minimum Load Constraint: To prevent baseload plants from ramping down to unrealistic levels, minimum power output can not fall below a set fraction of peak power output.

$MIN_LOADING_{n,m,q}$

$$CONVgen_{n,m,q} + CONVP_{n,m,q} \geq CONVgen_{n,seasonpeak,q} \cdot minplantload_q$$

A.4.5 Constraints on Storage

Energy Balance: Energy discharged from storage type st in each area i or n must not exceed the energy used to charge storage—multiplied by the round-trip efficiency for type st generators—within a single season.

$ENERGY_FROM_GRID_STORAGE_{n,s,st}$

$$\sum_{m \in s} STORout_{n,m,st} \cdot H_m \leq \sum_{m \in s} STORin_{n,m,st} \cdot H_m \cdot STOR_RTE_{st}$$

Storage Dispatch Constraint: Ensures that storage capacity of type st —derated by the average forced outage rate for type st generators—is adequate to supply all charging power, discharging power, and operating reserve demanded in each time-slice m .

$STORE_FO_PO_GRID_{n,m,st}$

$$STORout_{n,m,st} + STORin_{n,m,st} + STOR_OR_{n,m,st} \leq (STOR_{n,st} + old_STOR_{n,st})(1 - FO_{st})(1 - PO_{m,st})$$

Storage Growth Constraint: These two constraints allocate new storage capacity (MW) to bins that have costs associated with them over and above the cost of the storage capacity itself. The bins are defined as a fraction of the national storage capacity at the start of the period.

$STORAGE_GROWTH_TOT_{st}$

$$\sum_n STOR_{n,st} \leq \sum_{storagebp} STORAGEBIN_{st,storagebp}$$

$STORAGE_GROWTH_BIN_{st,storagebp}$

$$STORAGEBIN_{st,storagebp} \leq STORAGEBINCAP_{st,storagebpt} \cdot BASE_STORAGE_{st};$$

A.4.6 Others

Hydropower Energy Constraint: Restricts the energy available from hydroelectric capacity to conform to the historical availability of water.

$$HYDRO_ENERGY_n \quad \sum_m CONVgen_{n,m,hydro} \leq Hen_n$$

California Coal Restriction: Western states can generate no more energy from coal or ogs (plants that are dirtier than gas-cc) than they can consume in-state. This is to prevent them from shipping coal-generated electricity to California.

$$CALIFORNIA_COAL_{WECCstates,m}$$

$$\sum_{dirty,n}^{n \in states} (CONVgen_{n,m,dirty} + CONVP_{n,m,dirty}) \leq \sum_n^{n \in states} L_{n,m}$$

Generation from Low Sulfur Coal: This constraint essentially adds all the coal used in the different time slices throughout the year into a single variable.

$$LOWSULCOAL_{n,q}$$

$$coalallowsul_{n,q \in coaltech} \leq \sum_m (CONVgen_{n,m,q} + CONVP_{n,m,q}) \cdot H_m$$

SO₂ Scrubbers Constraint: Combined capacity of the scrubbed and unscrubbed coal plants must be equal to the total of the two from the last period minus retirements. Furthermore, unscrubbed coal capacity can not exceed the unscrubbed capacity of the last period minus retirements. This allows the unscrubbed to become scrubbed, i.e., the unscrubbed capacity can decrease but the total can not. Scrubbed coal plants can be converted to cofiring via the same mechanism,

$$SCRUBBER_n$$

$$\begin{aligned} CONV_{n,scr} + CONV_{n,uns} + CONV_{n,cofire} &= CONVold_{n,scr} - CONVret_{n,scr} \\ &+ CONVold_{n,uns} - CONVret_{n,uns} \\ &+ CONVold_{n,cofire} \end{aligned}$$

-and-

$$CONV_{n,uns} \leq CONVold_{n,uns} - CONVret_{n,uns}$$

$$COFIRE_CAPACITY_n$$

$$CONV_{n,scr} + CONV_{n,cofire} \geq CONVold_{n,scr} - CONVret_{n,scr} + CONVold_{n,cofire}$$

Emissions Constraint: Ensures that the national annual emission of each pollutant (CO₂, SO₂, NO_x, Hg) by all generators is lower than a national cap.

$EMISSIONS_{pol}$

$$\begin{aligned}
LP_{pol} \geq & \sum_{n,m,q} (CONVgen_{n,m,q} + CONVP_{n,m,q}) \cdot H_m \cdot CONVpol_{q,pol} \cdot CHEatrate_q \\
& + \sum_{n,m} STORout_{n,m,st} \cdot STORpol_{st,pol} \cdot CHEatrate_{st} \\
& - \sum_{\substack{q,n,pol \\ pol=SO_2}} coallowsul_{n,q} \cdot CONVpol_{q,pol} \cdot CHEatrate_q \cdot coallowsul_{polred} \\
& - \sum_{bioclass,n} CofireGen_{bioclass,n} \cdot CHEatrate_{cofire} \cdot (CONVpol_{coal,pol} - CONVpol_{biomass,pol})
\end{aligned}$$

Geothermal Constraints: These constraints regulate the expansion of geothermal capacity. Regional capacity is constrained by a recoverable capacity supply curve. Geothermal capacity, as shown below, is linked directly to $CONV_{q,n}$ and, through it, the model's framework for dispatchable conventional technologies.

$GEO_THERMAL_GROWTH_n$

$$\begin{aligned}
CONV_{n,geothermal} - CONVold_{n,geothermal} &= \sum_{geoclass} GeoBin_{geoclass,n} \\
&+ \sum_{egsclass} GeoEGSbin_{egsclass,n}
\end{aligned}$$

$GEO_THERMAL_GROWTH_BIN_{geoclass,n}$

$$GeoBin_{geoclass,n} + GeoOld_{geoclass,n} \leq GeoMax_{geoclass,n}$$

$GEOEGS_GROWTH_BIN_{egsclass,n}$

$$GeoEGSbin_{egsclass,n} + GeoEGSold_{egsclass,n} \leq GeoEGSmax_{egsclass,n}$$

Biofuel Constraints: These constraints regulate the capacity expansion of dedicated biomass and coal-biomass cofiring plants. Total bio-fired generation is limited by a regional feedstock supply curve. In cofired plants, biomass can contribute up to 15% of the feedstock. Biomass, like geothermal, is linked directly to the conventional variables such as $CONV_{n,q}$ and $CONVgen_{n,m,q}$.

$BIOPOWER_GROWTH_n$

$$CONV_{n,biopower} - CONVold_{n,biopower} = \sum_{bioclass} BioBin_{bioclass,n}$$

$COFIRE_GENERATION_n$

$$\sum_{bioclass} CofireGen_{bioclass,n} \leq 0.15 \cdot \sum_{q,m} CONVgen_{n,m,cofire}$$

$BIOPOWER_GENERATION_{bioclass,n}$

$$\begin{aligned}
& BioGeneration_{bioclass,n} \cdot CHEatrate_{biopower} + \\
& CofireGen_{bioclass,n} \cdot CHEatrate_{cofire} \leq BioSupply_{bioclass,n}
\end{aligned}$$

A.5 Glossary of Parameters

This is a glossary of all parameters that appear in the objective function and constraints of the detailed model description.

α_k	The fraction of pre-2006 transmission line k 's capacity available to wind.	$CF_{c,l,m,l}$	Capacity factor by time-slice for new wind of at a class c , location l site in supply region i .
$BASE_CSP$	National CSP capacity at the start of the period. (MW)	$CF_{cCSP,m}$	Capacity factor by time-slice for new CSP at a class $cCSP$ site.
$BASE_CSP_inst_i$	Regional CSP capacity at the start of the period. (MW)	$CFO_{c,l,m,l}$	Average capacity factor of all existing type l , class c wind on pre-2006 lines in region i .
$BASETPCA$	National transmission capacity at the start of the period. (MW)	$CFO_{cCSP,m}$	Average capacity factor of all existing class $cCSP$ CSP on pre-2006 lines.
$BASE_WIND$	National wind capacity at the start of the period. (MW)	$CFTO_{c,l,m,l}$	Average capacity factor of all existing type l , class c wind on new lines in region i .
$BASE_WIND_inst_i$	Regional wind capacity at the start of the period. (MW)	$CFTO_{cCSP,m}$	Average capacity factor of all existing class $cCSP$ CSP on new lines.
$BioFeedstockLCOF_{bioclass,n}$	Levelized cost of feedstock at each step of the biomass supply curve.	CG_g	Increase in turbine price due to rapid growth in wind capacity. (\$/MW)
$BioSupply_{bioclass,n}$	Amount of feedstock available at a given step on the biomass supply curve.	$CGcsp_gCSP$	Increase in CSP plant cost due to rapid growth in CSP capacity. (\$/MW)
$CarbTax$	Amount of carbon tax. (\$/ton CO ₂)	$CGcspinst_gCSPinst$	Increase in CSP installation cost due to rapid growth in CSP capacity. (\$/MW)
CCC_q	Overnight capital cost of conventional generating capacity. (\$/MW)	$CGinst_ginst$	Increase in wind installation cost due to rapid growth in wind capacity. (\$/MW)
$CCONV_q$	Present value of the revenue required to pay the capital cost of conventional generating capacity (\$/MW) including interest, construction, finance, and taxes.	$CGStorage_{st,storagebp}$	Increase in storage cost due to rapid growth in storage capacity. (\$/MW)
$CCONVF_q$	Present value of the annual fixed operating costs over the evaluation period for conventional generating capacity. (\$/MW)	$CHeatRate_q$	Heat rate (inverse efficiency) of conventional technology. (MMbtu/MWh)
$CCONVV_{n,q}$	Present value over the evaluation period of the variable operating and fuel costs for generation from conventional capacity. (\$/MWh)	$CHeatrate_{st}$	Heat rate (inverse efficiency) of storage technology. (MMbtu/MWh)
$CCSP_{cCSP}$	Capital cost of class $cCSP$ CSP capacity. (\$/MW)	$CONVpol_{q,pol}$	Emissions of pollutant for each MWh of generation by conventional technology q . (ton/MWh)
$CCt_{q,g}$	The present value of the cost of transmitting 1 MWh of power for each of E years between balancing authorities n and p .	$CONVold_{n,q}$	Existing conventional generating capacity, prior to the current period. (MW)

$CONVret_{n,q}$	Retirements of aging conventional capacity in a given period.	$CSPRuc_{cCSP,i}$	Amount of solar resource available. (MW)
$Cost_Inst_Frac$	Fraction of wind farm capital cost assigned to installation rather than the turbines themselves.	$CSPTO_{cCSP,i,j}$	Existing class $cCSP$ CSP capacity on new transmission lines from region i to region j .
$cpop_{c,i,l}$	Fractional increase in wind capital cost due to population density.	$CSPTturO_{cCSP,i}$	Existing CSP capacity for which new transmission capacity was built. (MW)
CQS	Cost to modify a combustion turbine to provide a quick-start capability. (\$/MW)	$CSPturO_{cCSP,i}$	Existing CSP capacity that utilizes pre-2006 lines. (MW)
CRF	Capital recovery factor, i.e. the fraction of the capital cost of an investment that must be returned each year to earn a given rate of return if income taxes and financing are ignored.	$CSRV_{n,q}$	Present value of the variable cost of spinning reserve provided over the evaluation period (\$/MWh)
$cslope_{c,i,l}$	Fractional increase in wind capital cost per degree of topographical slope.	$CSTOR_{st}$	Capital cost of storage capacity. (\$/MW)
$CSP2G_{cCSP,i,cspscp}$	New class $cCSP$ CSP resource in region i available at interconnection cost step $cspscp$.	$Ctranadder_q$	Transmission cost adder by conventional technology. (\$/MW)
$CSP2GPTS_{cCSP,i,cspscp}$	Cost to build transmission from a CSP site to the closest available grid transmission capacity.	$CVmar_{c,i,rto}$	(Capacity Value - marginal) The effective load-carrying capacity of 1 MW at a new wind or solar farm at a class c site in region i delivered to an rto .
$CspCVmar_{cCSP,i,rto}$	(CSP Capacity Value - marginal) The effective load-carrying capacity of 1 MW at a new CSP plant at a class $cCSP$ site in region i delivered to an rto .	$CVold_{c,i,rto}$	(Capacity Value - old) The effective load-carrying capacity of all the wind or solar capacity installed in previous periods whose generation is transmitted to an rto .
$CspCVold_{cCSP,i,rto}$	(CSP Capacity Value - old) The effective load-carrying capacity of all the CSP capacity installed in previous periods whose generation is transmitted to an rto .	CW_c	Present value of the revenue required to pay for the capital cost of class c wind capacity—including interest during construction, finance, and taxes. (\$/MW)
$CSPGridConCost$	Cost to connect a CSP plant to the grid. (\$/MW)	$CWOM_c$	Present value of operations and maintenance costs over the evaluation period for wind capacity—including property taxes, insurance, and production tax credit. (\$/MWh)
$CSP_inregion_dis_{cCSP,j,escp}$	Levelized cost—from the $escp$ step of the supply curve—for building a transmission line from a CSP site to a load center in the same region.	$Distance_{i,j}$	Distance between regions. (miles)
$CSPO_{cCSP,i,j}$	Existing class $cCSP$ CSP capacity on pre-2006 transmission lines from region i to region j .	$Distance_{n,p}$	Distance between balancing authorities. (miles)
$CSPOM_{cCSP}$	Present value of operations and maintenance costs over the evaluation period for CSP capacity (\$/MW)	F_q	Fraction of capacity that can be available as quickstart.
		FO_q	Forced outage rate of technology q .
		$Fprice_{q,n}$	Cost of input fuel for given technology. (\$/MWh)

$FSRV_q$ Fraction of capacity available for spinning reserve.	Her_n Annual hydro energy available in balancing authority n . (MWh)
$FSTOR_{st}$ Present value of the annual fixed operating costs over the evaluation period for storage capacity. (\$/MW)	$L_{j,m}$ Load by region and time-slice. (MW)
$GeoAdder_{geoclass,n}$ Additional capital cost for recoverable geothermal capacity along supply curve. (\$/MW)	$L_{n,m}$ Load by balancing authority and time-slice. (MW)
$GeoEGSadder_{egsclass,n}$ Additional capital cost for recoverable geothermal capacity along supply curve. (\$/MW)	$L_{rto,m}$ Load by rto and time-slice. (MW)
$GeoEGSmax_{egsclass,n}$ Amount of recoverable capacity at a given step on the EGS supply curve. (MW)	$lowsuladd_LCF_n$ Present value of 20-year expected additional leveled cost of fuel for using low sulfur coal.
$GeoEGSold_{egsclass,n}$ Existing EGS capacity, prior to the current period. (MW)	$minplantload_q$ The minimum level at which a conventional technology can run.
$GeoMax_{geoclass,n}$ Amount of recoverable capacity at a given step on the geothermal supply curve. (MW)	$MW_inregion_dis_{c,j,escp}$ Levelized cost—from the $escp$ step of the supply curve—for building a transmission line from a wind site to a load center in the same region.
$GeoOld_{geoclass,n}$ Existing geothermal capacity, prior to the current period. (MW)	$NERCRM_r$ Reserve margin requirement in the nerc region containing each balancing authority.
$GridConCost$ cost to connect a wind farm or CSP plant to the grid. (\$/MW)	$nor2rto_{rto}$ The variance of the usual operating reserve requirement in RTO rto .
Gt_g A fractional multiplier on the national wind capacity that defines the national wind capacity in step g of the wind turbine price multiplier for rapid growth.	$NRRfrac$ The fraction of the normal reserve requirement.
$GtCSP_{gCSP}$ A fractional multiplier on the national CSP capacity that defines the national CSP capacity in step $gCSP$ of the CSP plant price multiplier for rapid growth.	$old_STOR_{n,st}$ Existing grid-based storage at the start of the period. (MW)
$GtCSPinst_{gCSPinst}$ A fractional multiplier on the CSP capacity in a region that defines the region's CSP capacity in step $gCSPinst$ of the CSP installation price multiplier for rapid growth.	$ORMAR_{c,i,rto,m}$ The operating reserve requirement induced by the marginal addition of one MW of class c wind or solar capacity in region i that is consumed in an rto .
$Gtinst_{ginst}$ A fractional multiplier on the wind capacity in a region that defines the region's wind capacity in step $ginst$ of the wind installation price multiplier for rapid growth.	P_n Peak load in balancing authority n . (MW)
H_m Number of hours per year in time-slice m .	P_{rto} Peak load in rto rto . (MW)
	$PcostFrac_q$ multiplier on the operating costs of conventional generating capacity for use as a peaker.
	PO_q planned outage rate
	$PostStamp_{ij}$ the number of balancing authorities that must be crossed to transmit wind between two supply regions.
	$qsfrac$ minimum fraction of operating reserve that can be met by quickstart technologies

<i>Resconfint</i> (Reserve Confidence Interval) Operating reserve minimum expressed in terms of the number of standard deviations of operating reserve required.	<i>TOWCOST</i> cost of wind transmission on pre-2006 lines (\$/MWh-mile)
<i>RPSfraction</i> national renewable portfolio standard level as a fraction of national electric generation.	<i>TNCOST</i> cost of new transmission lines (\$/MW-mile)
<i>RPSSCost</i> penalty imposed for not meeting the national RPS requirement. (\$/MWh)	<i>TNWCOST</i> cost to build a new transmission line. (\$/MW-mile)
<i>St_CSPPRSCost_{states}</i> penalty imposed for not meeting the state RPS requirement for solar. (\$/MWh)	<i>TPCA_Gt_{TPCA,g}</i> A fractional multiplier of the national transmission (MW) capacity <i>BASETPCA</i> used to establish the size of growth bin <i>tpca_g</i> .
<i>st_Invincent_{states}</i> Before-tax value of state-level investment incentive for wind. (\$/MW)	<i>TPCAO_{n,p}</i> The transmission capacity between <i>n</i> and <i>p</i> that existed at the start of the period.
<i>STORpol_{st,pol}</i> Emissions of pollutant for each MWh of generation by storage technology <i>st</i> . (ton/MWh)	<i>TWLOSSnew</i> The fraction of wind power lost in each mile of transmission, for new wind.
<i>STOR_RTE_{st}</i> round-trip efficiency for storage technologies	<i>TWLOSSold</i> The fraction of wind power lost in each mile of transmission, for existing wind.
<i>st_Prodinent_{states}</i> Before-tax value of state-level production incentive for wind. (\$/MW-yr)	<i>VSTOR_{st}</i> present value over the evaluation period of the variable operating and fuel costs for generation from storage capacity (\$/MWh)
<i>St_RPSfraction_{states}</i> state renewable portfolio standard level as a fraction of state electric generation.	<i>WO_{c,i,j,l}</i> Existing class <i>c</i> wind of type <i>l</i> on pre-2006 transmission lines from region <i>i</i> to region <i>j</i> .
<i>St_RPSSCost</i> penalty imposed for not meeting the state RPS requirement. (\$/MWh)	<i>WR2G_{c,i,l,wscp}</i> New class <i>c</i> wind resource of type <i>l</i> in region <i>i</i> available at step <i>wscp</i> on the supply curve. (MW)
<i>SurplusMar_{c,i,rto,m}</i> Fraction of renewable (wind or solar) output (from a new class <i>c</i> source in region <i>i</i> to <i>rto</i> <i>rto</i>) curtailed in time slice <i>m</i> because must-run conventionals plus renewable output exceeds load.	<i>WR2GPTS_{c,i,l,wscp}</i> Cost associated with step <i>wscp</i> on the supply curve to build transmission from a wind site in region <i>i</i> to the closest available grid transmission capacity. (\$/MW)
<i>SurplusOld_{rto,m}</i> Fraction of renewable (wind or solar) output from all existing sources feeding <i>rto</i> <i>rto</i> curtailed in time slice <i>m</i> because must-run conventionals plus renewable output exceeds load.	<i>WRuc_{c,i,l}</i> amount of wind resource available. (MW)
<i>Tk_k</i> Capacity of transmission line <i>k</i> . (MW)	<i>WTO_{c,i,j}</i> Existing class <i>c</i> wind on new transmission lines from region <i>i</i> to region <i>j</i> .
<i>TLOSS</i> Fraction of conventional power lost in each mile of transmission.	<i>WturO_{c,i,l}</i> Existing wind capacity that utilizes pre-2006 lines. (MW)
<i>TOCOST</i> cost for wind to use pre-2006 transmission lines (\$/MWh-mile)	<i>WTturO_{c,i,l}</i> Existing wind capacity for which new transmission capacity was built. (MW)
<i>TOR_{rto,m}</i> The operating reserve requirement induced by the load, conventional generation, and existing wind capacity in an <i>rto</i> . (MW)	

Appendix B Electricity Price Calculation

The electricity price in ReEDS is calculated after the optimization, based on the installed capacity and dispatch in that period. The output electricity price, reported by balancing area, is a weighted average of the electricity prices for each time-slice. Electricity prices within time slices are calculated differently depending on whether the region is a net-importer or -exporter.

$$ElecPrice_n = \frac{\sum_m \begin{cases} Pelec_{n,m} \cdot gen_{n,m} & \text{if } gen_{n,m} \geq load_{n,m}, \\ Pelec2_{n,m} \cdot load_{n,m} & \text{if } gen_{n,m} < load_{n,m}. \end{cases}}{\sum_m \begin{cases} gen_{n,m} & \text{if } gen_{n,m} \geq load_{n,m}, \\ load_{n,m} & \text{if } gen_{n,m} < load_{n,m}. \end{cases}}$$

$gen_{n,m}$ is generation in balancing area n in time-slice m . (MWh)

$load_{n,m}$ is the load in balancing area n in time-slice m . (MWh)

If the region is a net-exporter in timeslice m , $Pelec_{n,m}$, the unadorned cost of generation, is used as the price of electricity:

$$Pelec_{n,m} = pgen_{n,m} + NGTC_n$$

If the region is a net-importer in the timeslice, however, $Pelec2_{n,m}$ —which includes the price of imports, $pimports_{n,m}$ —is used as the price of electricity instead:

$$Pelec2_{n,m} = (gen_{n,m} \cdot pgen_{n,m} + (load_{n,m} - gen_{n,m}) \cdot pimports_{n,m}) / load_{n,m} + NGTC_n$$

$NGTC_n$ (Non-Generation Transaction Cost) is a scalar set after the first time period to normalize the calculated 2006 electricity prices with historical data. It represents components of the electricity price not explicitly represented in ReEDS (e.g. distribution costs, administration costs, etc.). (\$/MWh)

The price of generation, $pgen_{n,m}$ is calculated from various components: return on ratebase, O&M costs for renewable and conventional technologies, and fuel costs. Calculations of the components of $pgen_{n,m}$ are shown in a separate section below.

$$pgen_{n,m} = \left(Ratebase_n \cdot disc + WindOM_n + CSPOM_n + \sum_q CfixOMtot_{n,q} + \sum_{st} FSTORtot_{n,st} \right) / ngen_n + (CfuelvOM_{n,m} + STORfuelOM_{n,m}) / gen_{n,m}$$

$ngen_n = \sum_m gen_{n,m}$, total generation in area n , summed over time-slices. (MWh)

$disc$ is the real discount rate, 8.5% in the Base Case.

$Ratebase_n$: book value of all installed capacity in area n . (\$)

$WindOM_n$: O&M costs for all wind feeding balancing area n . (\$)

$CSPOM_n$: O&M costs for all CSP feeding balancing area n . (\$)

$CfixOMtot_{n,q}$: fixed O&M costs for conventional technology q in area n . (\$)

$FSTORtot_{n,st}$: fixed O&M costs for storage technology st in area n . (\$)

$CfuelvOM_{n,m}$: variable O&M and fuel costs for conv. in area n in time-slice m . (\$)

$STORfuelOM_{n,m}$: variable O&M and fuel costs for storage in area n , time-slice m . (\$)

The price of imports in region n , $pimports_{n,m}$, is calculated from the wheeling price, $pwheeled_{n,m}$, the cost of generation in source region p in time-slice m .

$$pimports_{n,m} = \frac{\sum_p CONV_{p,n,m} \cdot H_m \cdot (pwheeled_{p,m} + transcoe_{p,n})}{\sum_p CONV_{p,n,m} \cdot H_m}$$

$CONV_{p,n,m}$ is transmission of conventionals from balancing area p to n in time-slice m . (MW)

$pwheeled_{p,m}$ is the cost of electricity either generated in or transmitted through region p in time-slice m . (\$/MWh)

$transcoe_{p,n}$ is a cost adder for transmission. (\$/MWh)

The Components of pgen

$Ratebase_{y,n}$ is the book value of all installed capacity in balancing area n in time period y .

$$Ratebase_{y_o,n} = Ratebase_{y_o-1,n} + Investment_{y_o,n} - .066 \cdot Ratebase_{2006,n} - \sum_{y_o-lt/2 < y < y_o} .066 \cdot Investment_{y,n}$$

(n.b. We only subtract off the 2006 Ratebase piece through 2036.)

y_o is the time period (year).

lt is the investment lifetime, 30 years in the Base Case.

$Investment_{y,n}$ is the total capital investment (for wind, CSP, conventionals, and storage) in area n in period y .

WindOM_n: The total O&M costs for wind are simply capacity multiplied by the sum of the fixed and variable O&M costs for class c wind. An average O&M cost for existing wind in class c by region j is updated after each time period to account for new builds ($CWOMold_{c,j}$, $CWOMTold_{c,j}$). Many of the quantities in the following formulae are outputs from the optimization, so definitions and explanations can be found among the variables in Section A.2 or in the glossary, Section A.5.

$$WindOM_n = \sum_{c,i,j,l}^{j \in n} (WN_{c,i,j,l} + WTN_{c,i,j,l} + Wtur_inregion_{c,j,l}) \cdot CWOM_{c,l} + \sum_{c,i,j,l}^{j \in n} (WO_{c,i,j,l} \cdot CWOMold_{c,j,l} + WTO_{c,i,j,l} \cdot CWOMTold_{c,j,l})$$

CspOM_n: O&M costs for CSP are calculated the same way as for wind:

$$CspOM_n = \sum_{cCSP,i,j}^{j \in n} (CspN_{cCSP,i,j} + CspTN_{cCSP,i,j} + CspTur_inregion_{cCSP,j}) \cdot CspOM_{cCSP} + \sum_{cCSP,i,j}^{j \in n} (CspO_{cCSP,i,j} \cdot CspOMold_{cCSP,j} + CspTO_{cCSP,i,j} \cdot CspOMTold_{cCSP,j})$$

CfixOMtot_{n,q}: The fixed O&M costs for conventionals are calculated by adding the costs for new capacity to the tracked expenses from existing capacity.

$$CfixOMtot_{n,q} = \sum_q CfixOM_{n,q} \cdot (CONV_{n,q} - CONVold_{n,q} - CONVret_{n,q}) \\ + CfixOMold_q \cdot CONVold_{n,q}$$

FSTORTot_{n,st}: Fixed O&M costs for storage are also calculated by adding costs for new installations to the previous time period's costs.

$$FSTORTot_{n,st} = \sum_{st} FSTORold_{n,st} \cdot old_STOR_{n,st} + FSTOR_{st} \cdot STOR_{n,st}$$

CfuelvOM_{n,m}, STORfuelOM_{n,m}: The variable O&M and fuel cost calculations use fuel prices for the period, not life cycle fuel costs, and include applicable carbon taxes.

$$CfuelvOM_{n,m} = \sum_q (CONVgen_{n,m,q} + CONVP_{n,m,q} \cdot Pcostfrac) \cdot H_m \cdot \\ (CConvVOMold_{n,q} + Heatrateold_{n,q} \cdot (Fprice_{n,q} + CarbTax \cdot CONVpol_{q,CO2}))$$

$$STORfuelOM_{n,m} = \sum_{st} (STORout_{n,m,st} \cdot H_m \cdot \\ (VSTORold_{n,st} + StHeatrateold_{n,st} \cdot (Fprice_{n,st} + CarbTax \cdot STORpol_{st,CO2}))$$

Appendix C Elasticity Calculations

C.1 Fuel Price Elasticities

The prices and price projections for coal and natural gas used in ReEDS are subject to demand elasticities. Baseline price and fuel demand projections are inputs to the model, and between optimizations the computed usage from the previous period is compared with the latest forecast for that year to update both price and usage projections. The updated prices are then used in the following year's optimization (and the updated forecasts are then compared to the outcome of that optimization).

The baseline price and fuel demand projections and the elasticities are all based on the AEO reference scenario and one or more other AEO scenarios (e.g. carbon tax, high renewables). By this method the baseline projections and elasticities are self-consistent. Short-term and long-term elasticities differ to account for varying flexibility of price compensation—i.e. short-term behavioral adjustments vs. long-term infrastructure improvements.

Equations for the two fuels are identical, so only the calculations for natural gas will be shown below. The adjusted fuel price forecast, $GasCost_{y,y_o,r}$ (the first subscript, y , varies over the set of time-periods 2006-2050 while the second subscript, y_o , marks the current time-period; so the subscripts indicate that this is the forecast for natural gas price in year y as forecast in y_o), is calculated by applying short-term and long-term multipliers, $Delta_gasprice_{y_o,term}$, to the fuel price forecast determined for the preceeding period. ReEDS tracks a fuel price forecast for each NERC region, but only a national elasticity.

$$GasCost_{y,y_o,r} = \begin{cases} (1 + Delta_gasprice_{y_o,st}) \cdot GasCost_{y,y_o-1,r} & \text{if } y_o \leq y \leq y_o + shortterm, \\ (1 + Delta_gasprice_{y_o,lt}) \cdot GasCost_{y,y_o-1,r} & \text{if } y > y_o + shortterm. \end{cases}$$

where the percentage change for the gas price has been calculated as (actual - expected)/(expected):

$$Delta_gasprice_{y_o,term} = gasprice_elas_{term} \cdot \left(\frac{gas_usage_{y_o-1} - Fcast_Gasusage_elec_{y_o-1,y_o-1}}{Fcast_Gasusage_elec_{y_o-1,y_o-1} + Fcast_Gasusage_nonelec_{y_o-1}} \right)$$

where

$gasprice_elas_{term}$ are short-term and long-term elasticity coefficients—percentage change in price for each one percent change in demand.

$gas_usage_{y_o-1}$ is the actual demand in the previous time-slice, $y_o - 1$.

$Fcast_Gasusage_elec_{y_o-1,y_o-1}$ is the forecasted demand for the previous time-slice, $y_o - 1$ as forecast in the previous time-slice, $y_o - 1$.

$Fcast_Gasusage_nonelec_{y_o-1}$ is the demand outside the electric sector for the previous time-slice, $y_o - 1$. Non-electric demand is not included in ReEDS and is not adjusted from the baseline forecast.

The new demand forecast, likewise, is an adjustment of the previous year's demand forecast, again calculated from (actual - expected)/(expected). By adjusting the price and demand forecasts simultaneously, ReEDS keeps the two trajectories paired: a given year's price trajectory is matched with the corresponding usage forecast; when the demand varies from that forecast, both trajectories are recalculated based on the new information.

$$Fcast_gasusage_elec_{y,y_o} = Fcast_gasusage_elec_{y,y_o-1} \cdot \left(\frac{gas_usage_{y_o-1}}{Fcast_gasusage_elec_{y_o-1,y_o-1}} \right)$$

Note that all updates to the fuel price and demand forecasts only impact subsequent years of simulation because ReEDS solves every two year period individually and sequentially.

C.2 Demand Elasticities

Electricity demand, as exemplified by the average and peak load parameters, $L_{n,m}$ and P_n , respectively, in ReEDS is subject to price elasticity. There is a regional internal electricity price calculation in ReEDS that adjusts the load growth forecast based on changes in electricity price.

The elasticity calculations are inverted compared to the fuel price elasticities—because here demand is adjusted based on price instead of price being adjusted because of changes in demand—but are otherwise very similar. The load forecasts are adjusted from the previous year’s forecast via short-term and long-term multipliers, $\Delta_{demand_{r,term}}$, which are computed based on differences between expected and actual electricity prices. Where the fuel price elasticities were uniform nationally, electricity demand elasticities can vary among NERC regions. The demand elasticities were determined based on differences between alternative AEO scenarios (e.g. reference case vs. carbon tax or high fuel prices) and so are consistent with the baseline demand trajectory. As with the fuel price elasticities, these calculations are completed between optimizations, using results from the previous time period’s solution to generate data that is used in the next time period.

$$L_{y,y_o,n,m} = \begin{cases} (1 + \Delta_{demand_{y_o,n \in r,st}}) \cdot L_{y,y_o-1,n,m} & \text{if } y_o \leq y \leq y_o + \text{shortterm}, \\ (1 + \Delta_{demand_{y_o,n \in r,lt}}) \cdot L_{y,y_o-1,n,m} & \text{if } y > y_o + \text{shortterm}. \end{cases}$$

$$P_{y,y_o,n} = \begin{cases} (1 + \Delta_{demand_{y_o,n \in r,st}}) \cdot P_{y,y_o-1,n} & \text{if } y_o \leq y \leq y_o + \text{shortterm}, \\ (1 + \Delta_{demand_{y_o,n \in r,lt}}) \cdot P_{y,y_o-1,n} & \text{if } y > y_o + \text{shortterm}. \end{cases}$$

where the multipliers are calculated, again, as (actual - expected)/(expected):

$$\Delta_{demand_{y_o,r,term}} = demand_elas_{r,term} \cdot \left(\frac{elec_price_{y_o-1,r} - Fcast_elec_price_{y_o-1,y_o-1,r}}{Fcast_elec_price_{y_o-1,y_o-1,r}} \right)$$

where

$demand_elas_{r,term}$ are short-term and long-term elasticity coefficients—percentage change in price for each one percent change in demand—for NERC region r .

$elec_price_{y_o-1,r}$ is the regional average electricity price computed in the previous time-slice, $y_o - 1$.

$Fcast_elec_price_{y_o-1,y_o-1,r}$ is the regional average electricity price for the previous time-slice, $y_o - 1$ as forecast in the previous time-slice, $y_o - 1$.

Appendix D Resource Variability Parameters

There are three basic resource variability parameters for renewables with variable resources (i.e. wind and solar) that are calculated for each period in ReEDS before the linear program optimization is conducted for that period. These include capacity value, operating reserve, and surplus. For each, a marginal value is calculated, which applies to new installations in the period, and an “old” value is calculated, which applies to all the capacity built in previous periods. This section describes the statistical assumptions and methods used to calculate these values.

These variable-resource parameters are calculated for a source from which the variable-resource renewable energy (VRRE) is generated and a sink to which the energy is supplied. The source is always a supply region. The user must specify the regional level for the sink. It can be a balancing authority (BA), a regional transmission organization (RTO), a NERC region, or an entire interconnect. The “old” values for these variable-resource parameters are calculated for each sink but not for each source since the old value is a single value for all the variable resource supplied to the sink.

D.1 Data inputs for the calculation of resource variability parameters

The inputs required for calculating the resource variability parameters describe the probability distributions associated with loads, conventional generator availability, and VRRE generation. For each, an expected value and standard deviation are calculated.

For loads the expected value, μ_L , is the same as the values used in the “LOAD_PCA” constraint. The standard deviation of the load, σ_L , is found from the load-duration curve of the sink region.

For conventional generator availability, the expected value is the nameplate capacity times 1 minus the forced outage rate.

$$\mu_C = \sum_q \text{CONVCAP}_{q,r} \cdot (1 - fo_q)$$

Variance of conventional generator availability is calculated thus:

$$\sigma_C^2 = \sum_q \text{numplants}_{q,r} \cdot \text{plantsize}_q^2 \cdot fo_q \cdot (1 - fo_q)$$

where

$$\begin{aligned} \text{plantsize}_q &\text{ is the input typical size of a generator of type } q \\ \text{numplants}_{q,reg} &= \text{CONVCAP}_{q,r} / \text{plantsize}_q \end{aligned}$$

The probability distribution associated with conventional generator availability is complicated by the fact that there can be many conventional generators and each one’s availability is a binomial random variable with probability $(1 - fo_q)$ of being one. We largely avoid this complication by first combining the random variables for conventional generator availability, C, with loads, L, in the form of a random variable X where:

$$X = C - L$$

The expected value of X, μ_X , is the sum of the expected values of the other two random variables

$$\mu_X = \mu_C - \mu_L$$

and, since C and L are statistically independent:

$$\sigma_X^2 = \sigma_C^2 + \sigma_L^2$$

$$\sigma_X = \sqrt{\sigma_C^2 + \sigma_L^2}$$

where σ denotes standard deviation and σ^2 is the variance.

Future improvements in the performance of wind and solar technologies are captured in ReEDS through increased capacity factors. These improved capacity factors translate directly into improvements in the mean of a VRRE plant's generation output. ReEDS also estimates a new standard deviation for a VRRE plant based on regressions that estimate the new standard deviation as a function of the old standard deviation and the new capacity factor.

In the variable-resource parameters described below the input distributions must represent the generation from all VRRE plants contributing to a sink region, not simply a single plant. The mean value μ_R is easily calculated as the sum of the mean values of the output of the individual contributing VRRE plants. The standard deviation is complicated by the fact that the outputs of the VRRE plants are correlated with one another. For each ReEDS time slice, we have used the WSIS data to develop a correlation matrix (P_{kl}) of the Pearson correlation between each possible pair k, l of region, class, and VRRE, e.g. a correlation coefficient represents the power output between class 5 wind in region 3 and class 2 PV generation in region 14. This P_{kl} matrix is an input to ReEDS. (Currently, correlation coefficients have only been calculated for wind to wind correlations, however, we are in the process of calculating wind-load, csp-csp, wind-csp, and csp-load correlations.) The variance of the VRRE arriving at a sink region r ($\sigma_{R_r}^2$) is then calculated from this correlation matrix P_{kl} through the standard statistical formula:

$$\sigma_{R_r}^2 = \sum_{k \in R_r} \sum_{l \in R_r} P_{kl} \cdot \sigma_k \cdot \sigma_l$$

where

R_r is the set of VRRE's contributing to region r

Armed with the mean and standard deviation of all VRRE contributing to a region r , we can now calculate the variable-resource parameters - capacity value, operating reserve, and surplus. In the current version of ReEDS, we assume all combined random variables to be normally distributed, though the distribution for each individual random variable (e.g. C, L, R_r) need not be normally distributed. For example, X is assumed to follow a normal distribution defined by it's mean, μ_X , and standard deviation, σ_X . The normal distribution approximation improves in accord with the central limit theorem. We also have the capability of using other probability distributions, e.g. Beta function.

D.2 Capacity Value

This is the capacity credit given to the VRRE contribution to meeting the reserve margin constraint in each sink region. It is a function of the amount and type of VRREs consumed in the sink region, the dispersion of the VRRE plants contributing the energy, the electric load in the sink region, the variability of the load and the amount and reliability of conventional capacity contributing to the load in the sink region. Generally, as more VRREs are used by the sink region, their capacity value decreases. And as more renewable energy from a particular source is used, the marginal capacity value from that source decreases.

CVold_r: For the total VRRE generation that is to be consumed in sink region r , the capacity credit, $CVold_r$, is the amount of load that can be added in every hour without changing the

system reliability in sink region r , i.e. without changing the loss-of-load probability. This added load is the effective load-carrying capability (ELCC) associated with the VRRE contributed to the sink region.

To estimate $CVold_r$, we first equate the loss of load probabilities of the random variables:

$$\begin{aligned} U &= C + R_r - L \\ V &= C - (L - \Delta_L), \end{aligned}$$

where C , R_r , and L are as defined above and Δ_L is the ELCC for the VRRE in the system. Assuming C , R_r , and L are statistically independent, the variances of U and V are given by:

$$\begin{aligned} \sigma_U^2 &= \sigma_C^2 + \sigma_{R_r}^2 + \sigma_L^2 \\ \sigma_V^2 &= \sigma_C^2 + \sigma_{L-\Delta_L}^2. \end{aligned}$$

The loss of load probability with VRRE in the system is the probability that U is less than zero or $P(U < 0)$. Define $U' = (U - \mu_U)/\sigma_U$ as a standard normal variable. The probability that U is less than zero is the probability that U' is less than $-\mu_U/\sigma_U$ or $N(-\mu_U/\sigma_U)$, where N is the cumulative standard normal distribution function. Similarly, $P(V < 0) = N(-\mu_V/\sigma_V)$ and the ELCC or Δ_L can be estimated by equating $P(U < 0) = P(V < 0)$. With these definitions, $CVold_r$ is simply Δ_L/TR_r where TR_r is the total installed VRRE nameplate capacity devoted to region r . The following shows the derivation for an expression for $CVold_r$.

$$\begin{aligned} P(V < 0) &= P(U < 0) \\ N(-\mu_V/\sigma_V) &= N(-\mu_U/\sigma_U) \\ \mu_V/\sigma_V &= \mu_U/\sigma_U \\ (\mu_C - \mu_L + \mu_{\Delta_L})/\sigma_V &= \mu_U/\sigma_U \\ \mu_{\Delta_L} &= \mu_L - \mu_C + \mu_U \cdot \sigma_V/\sigma_U \\ \Delta_L &= \mu_L - \mu_C + \mu_U \cdot \sigma_V/\sigma_U, \end{aligned}$$

where in the last equation we set $\Delta_L = \mu_{\Delta_L}$. Since μ_V is a function of $\sigma_{L-\Delta_L}^2$, which in turn depends on Δ_L itself, the above equation would be non-trivial to solve and would likely increase the run-time significantly. Instead of solving exactly, we estimate $\sigma_{L-\Delta_L}^2$ based on the ELCC or Δ_L of previous periods and use the result to find:

$$CVold_r = CF_r - \mu_U \cdot (1 - \sigma_V/\sigma_U)/TR_r,$$

where CF_r is the average capacity factor of the VRRE in the system and is defined by $CF_r = \mu_{R_r}/TR_r$.

$CVmar_{c,i,r}$ is the marginal capacity value associated with the addition of class c VRRE capacity in a source region i delivered to a sink region r . The calculation for $CVmar_{c,i,r}$ is very similar to the one for $CVold_r$. $CVmar_{c,i,r}$ is calculated using the random variable U above and the random variable

$$W = C + (R_r + \delta_{R_r,c,i}) - (L + \delta_L),$$

where $\delta_{R_r,c,i}$ is an incremental amount of class c VRRE from region i that can serve region r , and δ_L is the effective load carrying capacity for this increment of VRRE. δ_L is calculated similarly to the calculation for Δ_L above:

$$\begin{aligned}
P(W < 0) &= P(U < 0) \\
N(-\mu_W/\sigma_W) &= N(-\mu_U/\sigma_U) \\
\mu_W/\sigma_W &= \mu_U/\sigma_U \\
(\mu_C + \mu_{R_r} + \mu_{\delta_{R_r,c,i}} - \mu_L + \mu_{\delta_L})/\sigma_W &= \mu_U/\sigma_U \\
\mu_{\delta_L} &= \mu_C + \mu_{R_r} + \mu_{\delta_{R_r,c,i}} - \mu_L - \mu_U \cdot \sigma_W/\sigma_U.
\end{aligned}$$

Finally, $CVmar_{c,i,r}$ is equal to $\delta_L/\delta_{R_r,c,i}$ or equivalently,

$$CVmar_{c,i,r} = CF_{c,i} - \left(\frac{\sigma_W}{\sigma_U} - 1\right) \cdot \mu_U/\delta_{R_r,c,i}.$$

D.3 Operating Reserve Requirement

Operating reserve includes spinning reserve, quick-start capability, and interruptible load that can be dispatched to meet unanticipated changes in loads and/or power availability. There is no standard approach for estimating the level of operating reserve required. Some NERC regions assume that operating reserve must be at least as large as the largest single system contingency, e.g. the failure of a nuclear power plant. Others have reasoned that a system should have enough operating reserve to meet 7% of peak load (reduced if hydro is available). We assume in ReEDS that the normal operating reserve ($NOR_{r,m}$) required by a sink region r is proportional to the load ($L_{r,m}$) and conventional generation ($G_{r,m}$) in the region.

VRREs can induce a need for additional operating reserve beyond the usual requirement. ReEDS calculates the total operating reserves induced by all load, conventional generation, and VRREs in the system ($TOR_{r,m}$) and the operating reserves induced at the margin ($ORmar_{r,m}$) by the addition of an increment of VRRE capacity.

$TOR_{r,m}$ is the total operating reserve required in region r due to load, conventional generation, and all existing VRRE capacity contributing to sink region r (R_r). By assuming that the normal operating reserve is a 2-sigma reserve, we can estimate the sigma, $\sigma_{NOR_{r,m}}$, associated with the normal system operation (operating reserve required for load and conventional generation) as:

$$\begin{aligned}
NOR_{r,m} &= \frac{0.03 \cdot (L_{r,m} + G_{r,m})}{2 \cdot L_{r,m}} \\
\sigma_{NOR_{r,m}} &= NOR_{r,m} \cdot (L_{r,m} - R_r)
\end{aligned}$$

Since the normal system issues that require the normal operating reserve occur independently of the resource variability of VRREs, the variances of the two can be added to give the variance of the total. The total operating reserve is then assumed to be twice the standard deviation of the total.

$$TOR_{r,m} = 2 \cdot \sqrt{\sigma_{NOR_{r,m}}^2 + \sigma_{R_r}^2}$$

where

σ_{R_r} is assumed to be the standard variation of the output of all existing VRREs contributing to sink region r .

$ORmar_{c,i,r}$ is the marginal operating reserve requirement induced by the next MW of class c VRRE installed in region i that contributes generation to sink region r . It is calculated as the difference in the operating reserve required with an increment $\Delta R_{c,i,r}$ of additional VRRE capacity, minus that required with only the existing VRRE with the difference divided by the incremental VRRE capacity $\Delta R_{c,i,r}$.

$$ORmar_{c,i,r,m} = \frac{2}{\Delta R_{c,i,r}} \cdot \left(\sqrt{\sigma_{NOR,m}^2 + \sigma_{R_r + \Delta R_{c,i,r}}^2} - \sqrt{\sigma_{NOR,m}^2 + \sigma_{R_r}^2} \right)$$

D.4 Surplus

At high levels of VRRE penetration, there are times when the VRRE generation exceeds that which can be used in the system. This “surplus” VRRE generation must then be curtailed. ReEDS calculates the fraction of VRRE generation from existing VRRE plants (*Surplusold_r*) that is surplus as well as the fraction of generation from new VRRE plants (*Surplusmar_r*) that is surplus. ReEDS uses these surplus values to reduce the useful energy contributed by VRREs, making them less cost-effective generators.

SurplusOld_r is the expected fraction of generation from all the VRREs consumed in sink region r that cannot be productively used, because the load is not large enough to absorb both the VRRE generation and the must-run generation from existing conventional sources. This situation occurs most frequently in the middle of the night when loads are small, base-load conventional plants are running at their minimum levels, and the wind is blowing.

To calculate *Surplusold_r*, we use the random variable Y defined in the capacity value discussion above as the must-run conventional base-load generation M minus the load L plus the VRRE generation R .

$$Y = M - L + R$$

Next, we define the surplus VRRE at any point in time, S , as

$$\text{If } Y < 0, S = 0$$

$$\text{If } Y > 0, S = Y$$

Then the expected surplus μ_S can be calculated from the density function of Y , $g(y)$ as follows:

$$\begin{aligned} \mu_S &= \int_{-\infty}^{\infty} sf(s)ds \\ \mu_S &= \int_{-\infty}^0 sf(s)ds + \int_0^{\infty} sf(s)ds \\ \mu_S &= 0 + \int_0^{\infty} yg(y)dy \end{aligned}$$

The density function of y can be found by convolving the density function of $M - L$ together with the density function of the VRRE. However, similar to that which was done in the calculation of the VRRE capacity value above, we approximate normal distributions for both $M - L$ and R . With the normal distribution assumption, the value of μ_S can be quickly found in ReEDS with the analytical formula derived below:

Now if we assume, as we did in the *CVmar* and *ORmar* calculations above, that by the central limit theorem, Y can be well approximated by a normal distribution, and we define the

standard normal variable Y' as $Y' = (Y - \mu_Y)/\sigma_Y$, then

$$Y = Y' \cdot \sigma_Y + \mu_Y, \text{ and}$$

$$dY = \sigma_Y dY'$$

Thus

$$\begin{aligned}\mu_S &= \int_0^\infty yg(y)dy \\ \mu_S &= \int_{-\mu_Y/\sigma_Y}^\infty (y'\sigma_Y + \mu_Y) \cdot g(y'\sigma_Y + \mu_Y) \cdot \sigma_Y dy' \\ \mu_S &= \int_{-\mu_Y/\sigma_Y}^\infty \sigma_Y^2 \cdot y' \cdot g(y'\sigma_Y + \mu_Y) dy' + \int_{-\mu_Y/\sigma_Y}^\infty \mu_Y \cdot \sigma_Y \cdot g(y'\sigma_Y + \mu_Y) dy'\end{aligned}$$

Assuming Y is normally distributed, as stated above:

$$\begin{aligned}\mu_S &= \int_{-\mu_Y/\sigma_Y}^\infty \sigma_Y^2 \cdot y' \left(\frac{1}{\sigma_Y \sqrt{2\pi}} \right) \exp\left(\frac{(-y'\sigma_Y + \mu_Y - \mu_Y)^2}{2\sigma_Y^2} \right) dy' \\ &\quad + \int_{-\mu_Y/\sigma_Y}^\infty \mu_Y \cdot \sigma_Y \left(\frac{1}{\sigma_Y \sqrt{2\pi}} \right) \exp\left(\frac{(-y'\sigma_Y + \mu_Y - \mu_Y)^2}{2\sigma_Y^2} \right) dy' \\ \mu_S &= \int_{-\mu_Y/\sigma_Y}^\infty \frac{\sigma_Y \cdot y'}{\sqrt{2\pi}} \exp\left(\frac{-y'^2}{2} \right) dy' + \int_{-\mu_Y/\sigma_Y}^\infty \frac{\mu_Y}{\sqrt{2\pi}} \exp\left(\frac{-y'^2}{2} \right) dy' \\ \mu_S &= \frac{\sigma_Y}{\sqrt{2\pi}} \exp\left(\frac{-\mu_Y^2}{2\sigma_Y^2} \right) + \mu_Y \left(1 - N_{0,1}(-\mu_Y/\sigma_Y) \right)\end{aligned}$$

Where $N_{0,1}$ is the standard normal distribution with mean 0 and standard deviation 1.

Then $Surplusold_r$ is the difference between the expected surplus with VRRE, μ_S and the expected surplus were there no VRRE generation consumed in sink region r , μ_{SN} , divided by the total VRRE capacity contributing to sink region r , R_r . Or

$$Surplusold_r = (\mu_S - \mu_{SN})/R_r$$

Normally μ_{SN} would be zero, as the conventional must-run units would not be constructed in excess of the minimum load. However, with our assumption of a normal distribution for Y , we do introduce some non-zero probability that Y could be positive even if there were no VRREs, i.e. that the generation from must-run units could exceed load. Thus, it is important to calculate μ_{SN} and to subtract it from μ_S to remove the bulk of the error introduced by the normal distribution assumption. μ_{SN} is calculated in exactly the same way as μ_S , but with no VRREs included.

Must-run conventional capacity is defined as existing available (i.e., not in a forced outage state) coal and nuclear capacity in sink region r times a minimum turn-down fraction, $MTDF$. The expected value of the must-run capacity of type q available at any given point in time, μ_{M_q} , is thus:

$$\mu_{M_q} = CONVCAP_{q,r} * (1 - FO_q) * MTDF_q$$

where

$CONVCAP_{q,r}$ is the existing conventional capacity in sink region r of type q .

$MTDF_q$ is 0.45 for old (pre-2006) coal plants,

0.35 for new (post-2006) coal plants,

1.0 for nuclear plants.

SurplusMar_{c,i,r} is the fraction of generation from a small addition $\Delta R_{c,i,r}$ of class c VRRE installed in supply region i destined for sink region r that cannot be productively used because the load is not large enough to absorb both the VRRE generation and the must-run generation from existing conventional sources. It is calculated as:

$$Surplusmar_{c,i,r} = (\mu_{SR+\Delta R_{c,i,r}} - \mu_S) / \Delta R_{c,i,r}$$

Where $\mu_{SR+\Delta R_{c,i,r}}$ is calculated in exactly the same way as μ_S , but with $\Delta R_{c,i,r}$ MW of VRRE added in region i .

Appendix E Retirement of Capacity

All retiring wind turbines are assumed to be refurbished or replaced immediately, because the site is already developed with transmission access and other wind farm infrastructure. Wind capacity is replaced simply by assuming the wind capacity never decreases, i.e. the turbine capacity lasts indefinitely.¹¹ This does introduce a small error that is currently ignored. At the time that retiring wind turbines are replaced, they will most likely be replaced by state-of-the-art turbines, which can be expected to produce more energy and power per land area, and have higher capacity factors and lower costs than the machines they replace. This upgrading is not currently accounted for.

Similarly, storage at the wind site is assumed to be replaced immediately upon retirement. On the other hand, grid storage retires automatically when its assumed lifetime has elapsed.

Retirements of conventional generation can be modeled either as a fraction of remaining capacity each period (gas plants), through exogenous specification of planned retirements (currently used for nuclear, hydro, and oil/gas steam plants), or economic retirements (coal plants built before 2006).

Gas-fired Capacity Retirements: Because gas combustion turbines have been—and continue to be—used extensively as peaking plants, gas-CT capacity retirement is assumed to have reached a steady state condition, best modeled by assuming a fixed fraction of existing capacity is retired each year. The fraction retired is set equal to 1/assumed plant operational lifetime.

$$CONVRET_{n,CT} = CONVOLD_{n,CT} \cdot \left(\frac{2}{ltime_{CT}} \right)$$

After 2020, gas combined-cycle power plants are also retired at the fractional rate of 1/assumed plant operation lifetime. However, because such a high fraction of these plants were built in the four years between 2000 and 2004, the annual retirements before 2020 are restricted to 1/20 of the capacity that existed before 2006.

Nuclear, hydroelectricity, and oil/gas steam turbines: In reality, the retirement of these plants is determined by a host of factors other than their operational viability and economics. Thus, in ReEDS, where it is known that plants are scheduled to retire, that schedule is used. All capacity that does not have a scheduled retirement date is assumed to retire at a rate of 1/assumed plant operational lifetime.

$$CONVRET_{n,q} = PRETIRE_{n,q} + (CONVOLD_{n,q} - REMSCHED_{n,q}) \cdot \left(\frac{2}{ltime_q} \right)$$

Coal-fired capacity retirements: Existing coal plants are retired based on both their assumed operational lifetimes and their variable operating costs relative to the costs of constructing and operating new gas combined-cycle plants.

$$CONVRET_{n,q} = CONVOLD_{n,q} \cdot \left(\frac{2}{ltime_q} \right) \left(1 + \frac{CONRETkn_pgas_n}{VCcoal_{n,q}} \right)^{-3}$$

New coal plants are assumed to last beyond 2050, so there are no retirements of these plants.

¹¹In deciding whether to invest in wind, the model uses a 20-year evaluation period, i.e. the turbines are not assumed to last indefinitely.

Appendix F Financial Calculations

This section presents all the major financial parameters of ReEDS. It begins with general economic parameters that are used in the ReEDS economic calculations.

F.1 General Economic Parameters

Fundamental parameters

d , the real discount rate.

E , the evaluation period or investment lifetime, in years.

CRF , the capital recovery factor, is computed from d and E and represents the fraction of the capital cost of an investment that must be returned each year to earn a rate of return equal to d , ignoring income taxes and financing.

$$CRF = \left(\sum_{t=1}^E (1+d)^t \right)^{-1} = \frac{d}{1 - (1+d)^{-E}}$$

F.2 Financial Parameters Specific to Wind

This subsection includes many of the cost parameters that are calculated for wind.

CW_c is the present value of the revenue required to pay for the capital cost of one MW of wind capacity (\$/MW) including interest during construction, finance, and taxes.

$$CW_c = WCC_c \cdot \frac{IDC}{1 - TR} \cdot \left(\frac{(1 - FF) + FF \cdot PVDebt}{-TR \cdot (1 - ITCW/2) \cdot PVDep - ITCW} \right)$$

where

WCC_c is the overnight capital cost (\$/MW) of a class c wind plant. WCC_c can be either a direct input ($IWLC = 0$) or calculated based on a production learning curve ($IWLC = 1$). If learning-based improvements are allowed, then

$$WCC_c = WCC_c^0 \cdot \left(\begin{array}{l} (1 - costinstfrac)(1 - learnpar_{wind})^{\log_2 \left(WROW + \frac{WindCap_{T_delay}}{W_0} \right)} \\ + costinstfrac \cdot (1 - learnpar_{wind})^{\log_2 \left(\frac{WindCap_{T_delay}}{W_UScapyr2000} \right)} \end{array} \right)$$

where

WCC_c^0 is the overnight capital cost (\$/MW) of a class c wind plant without learning as input for the time period (i.e., includes any R&D driven changes over time, but not learning).

$costinstfrac$ is the fraction of the capital cost associated with installation.

$learnpar_{wind}$ is the learning parameter for wind, the % reduction in the capital cost of wind for each doubling of the installed capacity.

$WROW$ is the wind capacity installed in the rest of the world T_delay periods ago.

T_delay is the time required for learning to impact the market, i.e. the learning delay in periods between installations and cost reductions.

$WindCap_{T_delay}$ is the total national installed wind capacity T_delay periods ago.

$W_UScapyr2000$ is the total national capacity in the year 2000.

W_o is the total world wind capacity in the year 2000.

IDC is a multiplier to capture after-tax value of interest during construction.

$$IDC = \sum_{t=1}^{CP} CONSF_t \cdot \left(1 + (1 - TR) \cdot ((1 + i_c)^{CP-t} - 1) \right)$$

where

$CONSF_t$ is the fraction of the capital cost incurred in year t of construction.

i_c is the construction loan nominal interest rate.

CP is the construction period.

TR is the combined federal and state marginal income tax rate.

FF is the fraction of the plant capital cost financed. It can be input or calculated as shown below (see DSCR discussion) to ensure that the required debt service coverage ratio (DSCR) is met.

$ITCW$ = investment tax credit for wind.

$PVDebt$ is the after-tax present value of debt payments. ¹²

$$\begin{aligned} PVDebt &= \sum_{t=1}^L \frac{P_t + (1 - TR)I_t}{(1 + d_n)^t} \\ &= CRF_{i,L} \cdot (1 - TR) \cdot PVA_{d_n,L} + TR \cdot \left(\frac{CRF_{i,L} - i}{1 + i} \right) \cdot PVA_{d_n,L} \end{aligned}$$

where

¹²Closed-form expression for the after-tax present value of the loan payments. Define P_t as the principal payment in year t , and i as the nominal interest rate, then the cost of the loan payments over the life L of the loan is:

P_t is the principal portion of the finance payment made after the loan has been in place t years.

I_t is the interest portion of the finance payment made after the loan has been in place t years.

i = nominal interest rate for debt.

L = financing period.

$PVA_{d_n,L}$ is the present value of annual \$1 payments for L years.

$PVDep$ is the present value of depreciation

$$PVDep = \sum_{t=1}^{DP} \frac{Depf_t}{(1 + d_n)^t}$$

where

$Depf_t$ = depreciation fraction in year t

DP = depreciation period

$CWOM_c$ is the present value of E years of operating costs including property taxes, insurance, and production tax credit (\$/MW).

$$CWOM_c = WOMF_c \cdot PVA_{d,E} + 8760 \cdot CF_c \cdot (WOMV_c \cdot PVA_{d,E} - \frac{WPTC}{1 - TR} \cdot PVA_{d,PTCP})$$

where¹³

$WOMF_c$ is the fixed annual O&M cost of class c wind (\$/MW-yr)

$WOMV_c$ is the variable O&M cost of class c wind (\$/MWh)

$WPTC$ is the production tax credit (\$/MWh)

$PTCP$ is the period over which the production tax credit is received (years)

CG_g is the increase in turbine price over cost due to rapid growth in wind deployment. (\$/MW)

$$CG_1 = 0.01$$

$$CG_2 = (1 - Cost_Inst_Frac) \cdot CW_6 \cdot GP \cdot (BP_2 - BP_1)/2$$

$$CG_3 = (1 - Cost_Inst_Frac) \cdot CW_6 \cdot GP \cdot (BP_2 - BP_1 + (BP_3 - BP_2)/2)$$

$$CG_4 = (1 - Cost_Inst_Frac) \cdot CW_6 \cdot GP \cdot (BP_3 - BP_1 + (BP_4 - BP_3)/2)$$

$$CG_5 = (1 - Cost_Inst_Frac) \cdot CW_6 \cdot GP \cdot (BP_4 - BP_1 + (BP_5 - BP_4)/2)$$

$$CG_6 = (1 - Cost_Inst_Frac) \cdot CW_6 \cdot GP \cdot (BP_5 - BP_1)$$

where

CW_6 is the cost of a class 6 wind machine

GP is the growth penalty for each percent growth above the breakpoint

BP_k are breakpoints that discretize the growth price penalty:

$$(1 < BP_1 < BP_2 < BP_3 < BP_4 < BP_5 < BP_6)$$

¹³The use of a real discount rate in all the O&M calculations presumes that the O&M costs increase with inflation, i.e. that the real O&M cost is unchanging.

$CGinst_{ginst}$ is the increase in wind installation price over cost in growth bin $ginst$, due to rapid growth in wind deployment. (\$/MW)

$$CGinst_1 = 0.01$$

$$CGinst_2 = Cost_Inst_Frac \cdot CW_6 \cdot GPinst \cdot (BP_2 - BP_1)/2$$

$$CGinst_3 = Cost_Inst_Frac \cdot CW_6 \cdot GPinst \cdot (BP_2 - BP_1 + (BP_3 - BP_2)/2)$$

$$CGinst_4 = Cost_Inst_Frac \cdot CW_6 \cdot GPinst \cdot (BP_3 - BP_1 + (BP_4 - BP_3)/2)$$

$$CGinst_5 = Cost_Inst_Frac \cdot CW_6 \cdot GPinst \cdot (BP_4 - BP_1 + (BP_5 - BP_4)/2)$$

$$CGinst_6 = Cost_Inst_Frac \cdot CW_6 \cdot GPinst \cdot (BP_5 - BP_1)$$

where

$GPinst$ is the growth penalty for each percent growth above the breakpoint

F.3 Setting the Finance Fraction in ReEDS

The fraction of the capital cost of a wind farm that is financed can be input or endogenously estimated based on debt-service requirements. If calculated endogenously, the maximum fraction that can be financed is used. The fraction that can be financed is restricted by the Debt Service Coverage Ratio (DSCR). DSCR is the ratio of net pre-tax revenue to the debt payment (Debtpayment). ReEDS assumes the net pre-tax revenue is equal to the revenue required to recover capital cost plus profit and tax benefits (e.g., production tax credit).

$$DSCR = \frac{CRF_{d,E}}{Debtpayment} \cdot \left(CW_c + \frac{WPTC \cdot 8760 \cdot CF_c}{(1 - TR) \cdot PVA_{d,PTCP}} \right)$$

where

$$Debtpayment = FF \cdot WCC \cdot IDC \cdot CRF_{i,L}$$

Solving the DSCR equation for the finance fraction (which is embedded in CW_c , above) yields:

$$FF = CRF_{d,E} \cdot \frac{\frac{WPTC \cdot 8760 \cdot CF_c}{1 - TR} \cdot PVA_{d,PTCP} + \frac{WCC \cdot IDC}{1 - TR} \cdot \left(1 - TR \cdot \left(1 - \frac{ITCW}{2} \right) \cdot PVDep - ITCW \right)}{WCC \cdot IDC \cdot \left(DSCR \cdot CRF_{i,L} + \frac{(1 - PVDebt) \cdot CRF_{d,E}}{1 - TR} \right)}$$

F.4 Financial Parameters Specific to Conventional Technologies

This section includes many of the cost parameters that are calculated in ReEDS for conventional technologies. Inasmuch as some of these are substantively the same as those calculated for wind, the reader will be referred to the above wind parameter subsection.

$CCONV_q$ is the present value of the revenue required to pay for the capital cost of one MW of capacity of generating technology q (\$/MW) including interest during construction, finance, and taxes. It is calculated in a manner analogous to that for wind.

$$CCONV_q = CCC_c \cdot \frac{CRF_{d,E}}{CRF_{d,L_q}} \cdot \frac{IDC}{1 - TR} \cdot ((1 - FF) + FF \cdot PVDebt - TR \cdot (1 - ITC_q/2) \cdot PVDep - ITC_q)$$

where

CCC_c is the overnight capital cost (\$/MW) of the generation plant. CCC_c can be either a direct input ($ILC = 0$) or calculated based on a production learning curve ($ILC = 1$). If learning-based improvements are allowed, then

$$CCC_c = CCC_0 \cdot (1 - costinstfrac)(1 - learnpar_{wind})^{\log_2 \left(\frac{CONVOLDdelay_q}{USCapyr2000_q} \right)}$$

where

CCC_0 is the overnight capital cost (\$/MW) of generating technology without learning as input for the time period (i.e., includes any R&D driven changes over time, but not learning).

$CONVOLDdelay_q$ is the learning delay between installations and cost reductions.

$learndelay$ is the learning delay between installations and cost reductions.

$learnpar_q$ is the learning parameter for generation technology q , the % reduction in the capital cost for each doubling of the installed capacity.

$UScapyr2000_q$ is the total national capacity of generation technology q in the year 2000.

L_q is the economic lifetime of technology q (years).

FF is the finance fraction which must be input for conventional technologies (unlike the endogenous calculation option for wind described above).

See the calculation of CW_c for the definition of the other inputs for CCC_q

$CCONVV_{n,q}$ is the present value of the variable cost of operating technology q in balancing authority n for E years.

$$CCONVV_{n,q} = CVarOM_q \cdot PVA_{d,E} + Fprice_{q,n} \cdot chestrate_q \cdot PVA(n, q)_{d,E,e}$$

where

$CvarOM_q$ is the variable O&M cost for technology q (\$/MWh).

$Fprice_{q,n}$ is the cost of the input fuel (\$/MMBtu).

$chestrate_q$ is the heat rate for technology q .

$CCONVF_q$ is the present value of the fixed costs of operating technology q for E years (\$/MW).

$$CCONVF_q = COMF_q \cdot PVA_{d,E}$$

where

$COMF_q$ is the annual fixed O&M cost for plant type q (\$/MW-yr).

$CSRV_{n,q}$ is the present value of the variable cost of spinning reserve provided for E years in balancing authority n (\$/MWh). The cost represents the cost of operating the plant at part-load. A linear program can not ordinarily capture part-load efficiency, because it is highly nonlinear with the level of operation. ReEDS assumes that if spinning reserve is provided, the maximum amount is provided in the time-slice, the plant is operating

at $MinSR_q \cdot CONV_{n,q}$. Thus, the cost of spinning reserve can be estimated by solving the following for $CSRV_{n,q}$:

$$CCONVV_{n,q} \cdot \frac{MinSR_q \cdot CONV_{n,q}}{PLEffFactor_q} = CCONVV_{n,q} \cdot MinSR_q \cdot CONV_{n,q} + (1 - MinSR_q) \cdot CONV_{n,q} \cdot CSRV_{n,q}$$

or

$$CSRV_{n,q} = \frac{MinSR_q}{1 - MinSR_q} \cdot CCONVV_{q,n} \cdot \left(\frac{1}{PLEffFactor_q} - 1 \right)$$

F.5 Transmission Cost Parameters

$CCT_{n,p}$ is the present value of transmitting 1 MWh of power for each of E years between balancing authorities n and p (\$/MWh).

$$CCT_{n,p} = (Dis_{n,p} \cdot TOCOST + POSTSTWCOST \cdot PostStamp_{n,p}) \cdot PVA_{d_n,E}$$

where

$Dis_{n,p}$ is the distance in miles between the center of balancing authorities n and p.

$TOCOST$ is the cost per mile for using existing transmission lines (\$/MWh-mile).

$POSTSTWCOST$ is the cost of using transmission that crosses a balancing authority (\$/MWh).

$PostStamp_{n,p}$ is the number of balancing authorities that must be crossed to move from n to p. If p is adjacent to n, getting to p is considered to be crossing one balancing authority.

$TN_CG_{tn_g}$ is the difference between the price and cost of transmission in transmission growth bin tn_g (\$/MW-mile).

$$\begin{aligned} TN_CG_1 &= 0.01 \\ TN_CG_2 &= TNCost \cdot TNGP \cdot (TNBP_2 - TNBP_1)/2 \\ TN_CG_3 &= TNCost \cdot TNGP \cdot (TNBP_2 - TNBP_1) + (TNBP_3 - TNBP_2))/2) \\ TN_CG_4 &= TNCost \cdot TNGP \cdot (TNBP_3 - TNBP_1) + (TNBP_4 - TNBP_3))/2) \\ TN_CG_5 &= TNCost \cdot TNGP \cdot (TNBP_4 - TNBP_1) + (TNBP_5 - TNBP_4))/2) \\ TN_CG_6 &= TNCost \cdot TNGP \cdot (TNBP_5 - TNBP_1) \end{aligned}$$

where

$TNCost$ is the cost per mile of building new transmission lines (\$/MW-mile).

$TNGP$ is the percent increase in the cost of transmission for each percent growth over the base amount.

$TNBP_k$ are breakpoints that discretize the growth price penalty:
 $(1 < TNBP_1 < TNBP_2 < TNBP_3 < TNBP_4 < TNBP_5 < TNBP_6)$

Appendix G Geographic Information System (GIS) Calculations

Using Geographic Information Systems (GIS), a preliminary optimization is performed outside and prior to the linear programming model to construct a supply curve for onshore wind, shallow offshore wind, and deep offshore wind for each region i and wind class c .

The pre-optimization minimizes:

$$\sum_{c,i,l,h,k} (GC_{c,l} + TC_{c,i,l,h,k}) \cdot W_{c,i,l,h,k} + \sum_k M \cdot D_k$$

Subject to:

$$\sum_{c,i,l,h,k} W_{c,i,l,h,k} + D_k \leq a_k \cdot T_k$$

where

$GC_{c,l}$ is the levelized cost of generation from a wind farm of type l at a class c wind resource site.

$TC_{c,i,l,h,k}$ is the levelized cost of building a transmission spur for class c wind of type l from grid square h in region i to transmission line k .

$W_{c,i,l,h,k}$ is class c wind of type l transported from grid square h in region i on transmission line k .

M is a large number (very high cost).

D_k is a dummy variable to ensure feasibility in the constraint below.

a_k is the fraction of the capacity (T_k) of line k available

Using the results of this pre-optimization, supply curves are constructed for each region i , for each type of wind resource l (onshore, shallow offshore, and deep offshore) and for each class of wind resource within that type. Each supply curve is made up of four wind resource/cost pairs identified by the subscript $wscp$ where $wscp$ takes on the values 1 through 4. The amount of wind resource in each step is set initially so that for each type of wind l :

$$WR2G_{c,i,l,wscp} = f_{wscp} \cdot \sum_{h,k} W_{c,i,l,h,k}$$

$$\text{where: } f_i = 0.1 \cdot i$$

Thus, the first step on the supply curve is comprised of the 10% of all the class c wind grid squares in region i with the lowest cost to build transmission spurs to the grid. The next step consists of the 20% with the next lowest set of costs, etc. The cost, $WR2GPTS_{c,i,l,wscp}$, associated with each point or step on the supply curve is the mean levelized transmission spur cost for that step.

The supply curve quantity/price pairs— $WR2G_{c,i,l,wscp}$ and $WR2GPTS_{c,i,l,wscp}$ —from this pre-LP optimization are input to the linear programming ReEDS model within the “Wind Supply Curve” constraints. In each period, the quantities, $WR2G_{c,i,l,wscp}$, are decremented by the amount of wind resource in that step deployed in previous periods.

Ideally, this preoptimization should be performed for each period of the ReEDS run with the costs of wind generation specific to that period (wind generation costs generally decrease from one period to the next either because of exogenously specified R&D-driven reductions in capital and operating costs, and/or because of learning through industrial experience). This is not possible because of time and computer resources required to conduct this optimization in GIS for the large number of wind grid squares considered. Currently, the optimization is conducted once using the wind cost/performance characteristics for the first period.

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